







Article

A New Tool for Assessing Environmental Impacts of Altering Short-Term Flow and Water Level Regimes

María Dolores Bejarano ^{1,*}, Jaime H. García-Palacios ², Alvaro Sordo-Ward ², Luis Garrote ²
and Christer Nilsson ^{3,4}

¹ Department of Natural Systems and Resources, Universidad Politécnica de Madrid, 28040 Madrid, Spain

² Department of Civil Engineering; Hydraulics, Energy and Environment, Universidad Politécnica de Madrid, 28040 Madrid, Spain; jaime.garcia.palacios@upm.es (J.H.G.-P.); alvaro.sordo.ward@upm.es (A.S.-W.); l.garrote@upm.es (L.G.)

³ Landscape Ecology Group, Department of Ecology and Environmental Science, Umeå University, SE-901 87 Umeå, Sweden; christer.nilsson@umu.se

⁴ Department of Wildlife, Fish and Environmental Studies, Swedish University of Agricultural Sciences, SE-901 83 Umeå, Sweden

* Correspondence: mariadolores.bejarano@upm.es; Tel.: +34-910671778

Received: 13 September 2020; Accepted: 10 October 2020; Published: 19 October 2020



Abstract: The computational tool InSTHAN (indicators of short-term hydrological alteration) was developed to summarize data on subdaily stream flows or water levels into manageable, comprehensive and ecologically meaningful metrics, and to qualify and quantify their deviation from unaltered states. The pronunciation of the acronym refers to the recording interval of input data (i.e., instant). We compared InSTHAN with the tool COSH-Tool in a characterization of the subdaily flow variability of the Colorado River downstream from the Glen Canyon dam, and in an evaluation of the effects of the dam on this variability. Both tools captured the hydropeaking caused by a dam operation, but only InSTHAN quantified the alteration of key flow attributes, highlighting significant increases in the range of within-day flow variations and in their rates of change. This information is vital to evaluate the potential ecological consequences of the hydrological alteration, and whether they may be irreversible, making InSTHAN a key tool for river flow management.

Keywords: fluvial ecosystems; hydropeaking; InSTHAN tool; short-term flow regimes; subdaily flows; sustainable river management

1. Introduction

Flow variables shape the dynamics of in-channel and floodplain conditions that determine fluvial ecosystem structure and functioning [1,2]. Whereas the ecological role of monthly and annual flow dynamics has been in focus for many years, less attention has been paid to flow variability within days [3].

Variation at such short time scales is altered by several human activities, such as land use and urbanization, and water management practices such as flood control, agricultural withdrawals and power generation [4,5]. Increasing instability of within-day flows and exacerbation of extreme flows may likely affect water quality [6], fluvial landforms [7] and aquatic and riparian organisms that are adapted to naturally less fluctuating conditions (review by Bejarano et al., 2018 [8]).

Subdaily flow regimes govern fish reproduction [9] by affecting egg viability and reproductive capacity. They also affect their behavior [10] and performance [11] by offering shelter and food, which affects their movements. Ultimately, subdaily flow regimes affect fish survival, by modulating fish energy balance with implications for growth rates and risk of illness, or due to stranding and drift [12]. Risk of desiccation [13] and catastrophic drift [14] of macroinvertebrates increases with more

recurrent daily dry periods and peak flows. Highly fluctuating short-term flow regimes may also increase propagule dispersal of aquatic and riparian plants, and interfere with germination, growth and performance, thus likely hampering recruitment and increase mortality [15,16]. At the community level, alterations of short-term flows may ultimately result in removal of intolerant species and invasion by exotic species [17].

The rise of hydropower as a renewable energy source calls for a better understanding of the ecological consequences of altered flow regimes and associated hydraulic parameters at short time scales. Hydropeaking plants usually cause frequent and rapid fluctuations in flow and water level within the day [18], and this variation is superimposed upon the seasonal changes in flow regimes resulting from water storage in upstream reservoirs. The demand for hydropower is growing, especially in Southeast Asia, Africa and Latin America [19]. In Europe, hydropower is promoted by legislation such as the Renewable Energy Directive (RES; 82 2009/28/EC). Consequently, shifting flow regimes towards preindustrial conditions in rivers affected by hydropeaking without significantly affecting hydropower production is a challenge for river managers. To cope with this challenge, scientific studies focused on the short-term variation of flow regimes are needed.

The restoration of preindustrial flow regimes requires metrics comprising of the full range of flow components (i.e., magnitude, frequency, duration, timing and rise and fall rates; [1]) and temporal variability (i.e., long- and short-term variations) is essential. Whereas studies of seasonal and annual flow patterns have been common, analysis of short-term data have suffered from a lack of computational tools. To the best of our knowledge, the first metrics accounting for short-term variability of flow regimes appeared within the last two decades (e.g., [4]) and the most comprehensive approaches date from 2014 onwards (Table 1). Unlike the recent advance in the definition of subdaily metrics, computational tools supporting metric calculation have hardly been developed. The tools devised by Hass et al. [20] and Sauterleute and Charmasson [21] (Table 1) are the only ones we are aware of to date, and at the time of writing, the former tool was unavailable for use. This is unfortunate, because the management of series of flows or water levels recorded at such a fine resolution is challenging.

Our main goal is to develop a tool for computational time series analysis that assists in a comprehensive characterization of short-term stream flow and water level regimes and assesses the alterations of such regimes and, thus, their derived potential environmental impacts. We also want the tool to provide results through charts and graphs, which are easy to interpret by a wide range of users. Additionally, in this article we also aim to validate the devised tool by applying it to a case study. This manuscript will help to transmit the utility of the proposed tool to both the scientific and professional audience.

Table 1. Review of literature dealing with subdaily flows and water levels.

Reference	Time Interval between Records	Characteristics of the Subdaily Metrics	Characterization	Impact Assessment	Tool
Archer and Newson 2002 [2]	15 min	Metrics quantifying the frequency and duration of flow pulses per day	Yes	Yes	No
Topping et al., 2000 [22]	Several subdaily intervals	Metrics quantifying the subdaily discharge variability	Yes	Yes	No
White et al., 2005 [23]	1 h	Wavelet analysis	Yes	Yes	No
Meile et al. 2011 [24]	Any subdaily interval	Metrics quantifying the magnitude (maximum and minimum) and variability (ramping rate) of hourly flows per day	Yes	No	No
Zimmerman et al., 2010 [25]	1 h	Metrics quantifying magnitude (percentage of total flow), variation (coefficient of diel variation and flashiness) and frequency (reversals) of hourly flows per day	Yes	Yes	No
Bevelhimer et al., 2015 [26]	1 h	Metrics quantifying the magnitude (maximum, minimum and amplitude), variation (standard deviation, flashiness and maximum ramping rate) and frequency (reversals, rise and fall counts) of hourly flows per day	Yes	No	No
Haas et al., 2014 [20]	1 h	Statistics and metrics quantifying the variation (coefficient of variation, flashiness, rise and fall rates), magnitude (range), frequency and duration (path length) and timing (season) of hourly flows and flow pulses per day	Yes	No	Yes
Sauterleute and Charmasson 2014 [21]	Any subdaily interval	Metrics characterizing peaking events of subdaily flows or water levels through the magnitude (maximum and minimum), variation (rise and fall rate), timing (start time in the day), duration (duration between rapid increases or decreases) and frequency (counts of peaking events)	Yes	No	Yes
Carolli et al., 2015 [27]	1 h	Metrics related to the flow magnitude (maximum and minimum) and variation (a percentile of the discretized time derivative) of hourly flows per day	Yes	Yes	No
Chen et al., 2015 [28]	1 h	Metrics characterizing flow pulses per day by quantifying the magnitude (i.e., maximum and minimum), variation (i.e., maximum rise and fall rates), frequency (i.e., different or certain magnitude counts) and duration (i.e., duration of maximum and minimum)	Yes	Yes	No
Barbalić and Kuspilić 2015 [29]	1 h	Metrics quantifying the magnitude of hourly flows and associated water levels during a day (i.e., maximum and minimum)	Yes	Yes	No
Greimel et al., 2016 [30]	15 min	Metrics quantifying the duration, number and flow rates (i.e., maximum, mean and minimum) of flow events per day	Yes	No	No
Alonso et al., 2017 [31]	1 h	Graphical representation of commonly used metrics characterizing daily flow patterns based on hourly flow records related to the magnitude (i.e., amplitude), variation (i.e., fall rate) and frequency (i.e., reversals)	Yes	Yes	No
Bejarano et al., 2017 [32]	1 h	Metrics quantifying the magnitude (maximum, minimum and amplitude), variation (rise and fall rates), frequency (rise, fall and stability, minimum and maximum and reversals counts), duration (length of rise, fall and stability periods) and timing (day) of hourly flows per day	Yes	Yes	No
Ashraf et al. 2018 [33]	1 h	Two metrics that quantify the high-frequency variations at a given time and seasonal changes	Yes	No	No

2. Materials and Methods

2.1. InSTHAN's Development: Underlying Theory and Methods

We developed the new tool called InSTHAN: indicators of short-term hydrological alteration. InSTHAN allows the user to (i) summarize multiple, long series of subdaily flow or stage data into a manageable set of ecologically meaningful metrics (i.e., characterization), (ii) qualify and quantify the deviation of each series from the unaltered state to assess the hydrological alteration and its potential environmental impact and (iii) display both the short-term flow or stage pattern and its impact by using tables and graphs. The name informs on its ultimate purpose and time scale of the target regime. The pronunciation of the acronym refers to the required recording interval of the input data (i.e., instant flow or water level measured or modeled records).

2.1.1. Characterization of Short-Term Regimes

The first step when analyzing a subdaily flow or water level dataset is to describe its distinctive features. For this aim, the proposed tool computes a set of descriptors, here called short-term characterization indicators (STCI; Table 2). STCI meets two requirements: it (i) captures representative information on the magnitude, frequency, duration, timing and rates of change from the subdaily flow or water level dataset and (ii) is assumed relevant for the biotic composition of aquatic, wetland and riparian ecosystems [1,34].

Table 2. Short-term characterization indicators calculated in indicators of short-term hydrological alteration (InSTHAN). # means “number of”.

STCI Name and Abbreviation	Units	Group	STCI $366 \times n$ (366 Values per “n” Years)
Total Rise Records (TRR)	# records/day	Frequency	Within-day total records characterized by the rise in the variable
Total Fall Records (TFR)	# records/day	Frequency	Within-day total records characterized by the fall in the variable
Total Stability Records (TSR)	# records/day	Frequency	Within-day total records characterized by the stability in the variable
Total Change Records (TCR)	# records/day	Frequency	Within-day total records that are preceded and followed by different patterns in the variable
Total Reversals (TRev)	# reversals/day	Frequency	Within-day total times the hourly variable rises and falls
Total Minimum Records (TMinR)	# records/day	Frequency	Within-day total records when the variable equals that day's minimum
Total Maximum Records (TMaxR)	# records/day	Frequency	Within-day total records when the variable equals that day's maximum
Total Mean Records (TMeanR)	# records/day	Frequency	Within-day total records when the variable equals or exceeds that day's mean
Total Rise Periods (TRP)	# periods/day	Frequency	Within-day total periods characterized by a sustained over time rise in the variable
Total Fall Periods (TFP)	# periods/day	Frequency	Within-day total periods characterized by a sustained over time fall in the variable
Total Stability Periods (TSP)	# periods/day	Frequency	Within-day total periods characterized by a sustained over time stability in the variable
Total Stability Periods characterized by the Minimum (TMinSP)	# periods/day	Frequency	Within-day total periods characterized by a sustained over time that day's stability periods minimum
Total Stability Periods characterized by the Maximum (TMaxSP)	# periods/day	Frequency	Within-day total periods characterized by a sustained over time that day's stability periods maximum
Total Stability Periods characterized by the Mean (TMeanSP)	# periods/day	Frequency	Within-day total periods characterized by a sustained over time that day's stability periods mean

Table 2. Cont.

STCI Name and Abbreviation	Units	Group	STCI $366 \times n$ (366 Values per “n” Years)
Duration Rise Periods (DurRP)	# records/day	Duration	Within-day average duration of the periods characterized by a sustained over time rise in the variable
Duration Fall Periods (DurFP)	# records/day	Duration	Within-day average duration of the periods characterized by a sustained over time fall in the variable
Duration Stability Periods (DurSP)	# records/day	Duration	Within-day average duration of the periods characterized by a sustained over time stability in the variable
Duration Stability Periods characterized by the Minimum (DurMinSP)	# records/day	Duration	Within-day average duration of the periods characterized by a sustained over time that day’s stability periods minimum
Duration Stability Periods characterized by the Maximum (DurMaxSP)	# records/day	Duration	Within-day average duration of the periods characterized by a sustained over time that day’s stability periods maximum
Duration Stability Periods characterized by the Mean (DurMeanSP)	# records/day	Duration	Within-day average duration of the periods characterized by a sustained over time that day’s stability periods mean
Mean (Mean)	unitless or variable units	Magnitude	Within-day average of the variable
Standard Deviation (SD)	unitless or variable units	Magnitude	Within-day standard deviation of the variable
Minimum (Min)	unitless or variable units	Magnitude	Within-day minimum of the variable
Maximum (Max)	unitless or variable units	Magnitude	Within-day maximum of the variable
Amplitude (A)	unitless or variable units	Magnitude	Difference between within-day maximum and minimum of the variable
Minimum Stability Period (MinSP)	unitless or variable units	Magnitude	Within-day minimum of the periods characterized by a sustained over time stability in the variable
Maximum Stability Period (MaxSP)	unitless or variable units	Magnitude	Within-day maximum of the periods characterized by a sustained over time stability in the variable
Mean Stability Period (MeanSP)	unitless or variable units	Magnitude	Within-day mean of the periods characterized by a sustained over time stability in the variable
Rise Rate (RR)	variable units/T	Rate	Within-day average rise rate of the variable
Fall Rate (FR)	variable units/T	Rate	Within-day average fall rate of the variable

STCI was calculated based on an n -year long series of flows (Q) or water levels (L) recorded or modeled at any subdaily time scale, e.g., every 15, 30, 60 or 120 min, T being the time interval between records. Optionally, series of longer T can be derived from the original dataset upon request. For the purpose of defining indicators, each daily hydrograph (or limnograph) is divided into two characterization units: records (R ; e.g., Q or L records; Figure 1) and periods (P). The number of records (R) per day varies according to T , which can be the same as that of the series input at least. Each record (R) of a series can be assigned one of the following patterns: (1) rise (RR), when $Q_{(T)} - Q_{(T-1)} > 0$; (2) fall (FR), when $Q_{(T)} - Q_{(T-1)} < 0$; (3) stability (SR), when $Q_{(T)} - Q_{(T-1)} = 0$; (4) change (CR), when $Q_{(T-1)} \neq$ the pattern in $Q_{(T+1)}$; (5) reversal (RR), when the pattern changes from FR to RR or vice versa, without considering the stability; (6) minimum (MinR), when $Q_{(T)} = Q_{(\min)}$; (7) maximum (MaxR), when $Q_{(T)} = Q_{(\max)}$ and (8) mean (MeanR), when $Q_{(T)} = Q_{(\text{mean})}$. The threshold from which two consecutive records are considered different (or equal) may be set by the user. It could be similarly applied to L . Where T is the user-defined subdaily time interval and min, max and mean are the daily minimum, maximum and mean flows or water levels, respectively. Periods (P) denote

within-day portions of time of a similar pattern among records (cf. above). There may be one to several P per day, lasting up to 24 h, and which can be classified according to the characteristic short-term pattern into periods of rise (RP), fall (FP), stability (SP), minimum ($MinP$), maximum ($MaxP$) and mean ($MeanP$). STCI provides quantitative information on magnitudes, rates of change and frequencies of R and P and on durations of P , from each day of the year (i.e., i th day of the year from 1 to 366). That STCI has daily values also implies information on timing (i.e., intra-annual and inter-annual) of R and P . STCI referred to R patterns is called record-based STCI, whereas STCI referred to P patterns is named period-based STCI. For comparisons of several short-term regimes, the record-based STCI must be calculated based on the same time interval between records (T of their R) for all series (Table 2).

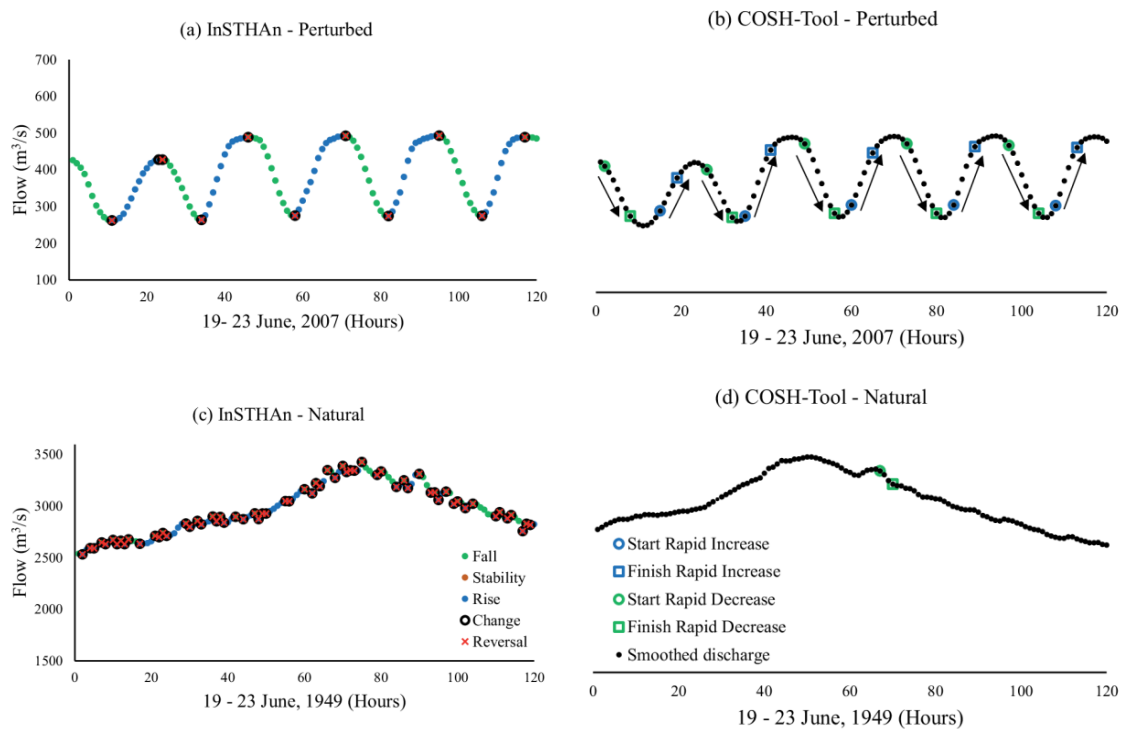


Figure 1. Patterns identified by InSTHAN (a,c; pre-dam) and COSH-Tool (b,d; post-dam) during five days in June, 2007 (a,b) and 1949 (c,d), in a hydrograph built on hourly flows recorded in the Colorado River reach downstream from the Glen Canyon dam. Dots represent the flow records, which are colored or marked according to their pattern for InSTHAN or to identify peaking events for COSH-Tool. The following figures were provided to COSH-Tool for peaking events identification: 4 and 96 as inferior and superior percentiles of the rate of change, 120 min as the minimum duration for a peak, 0.2 as the magnitude threshold to merge peaks and 180 min as the minimum duration between two consecutive peaks.

For several-year long series ($n > 1$; where j th denotes each year of the series from 1 to n), each indicator is ultimately computed as each day average for the whole n years dataset, getting 366 values per indicator (Equation (1); Table 2). The frequency and duration indicators report records a day of what it is being described by the indicator. Rate-related features report the rise or fall rates of the variable in its units per the time interval (T) between records (R). The units of the STCI magnitude-related indicators are the same of the selected variable (e.g., m^3/s for flows or m for levels). Furthermore, for the calculation of STCI describing magnitude-related features, the series is also previously standardized by dividing between the mean flow or water level for the whole dataset. Consequently, InSTHAN also provides unitless magnitude-related indicators, which is useful when

comparing series from different rivers. The tool calculates values for a total of 30 STCI, from which 14 are related to frequencies, 6 to durations and 10 to magnitudes and rates of change (Table 2).

$$STCI_{day(i)} = \frac{\sum_{j=1}^{j=n} STCI_{day(i,j)}}{n} \quad (1)$$

Equation (1): $STCI_{day(i)}$: short-term characterization indicator for the i th day from 1 to 366 of the year; $\sum_{j=1}^{j=n} STCI_{day(i,j)}$: sum of the short-term characterization indicator for the i th day from 1 to 366 of the year j th of the several-year long dataset from 1 to n and n : total number of years of the dataset.

2.1.2. Assessment of Short-Term Hydrological Alteration and Environmental Impact

When assessing the impact of a perturbation we want to know whether the state of the perturbed system differs significantly from what it would have been in the absence of perturbation (natural onwards). Provided the difficulties in collecting direct ecological data both under perturbed and natural conditions, the here proposed tool is based on the widespread qualitative understanding of the ecological implications of the suite of hydrological indicators calculated by InSTHAN to derive the potential environmental impact of the alteration of the short-term flow or water level regimes. That is, the environmental impact is assumed in accordance with the degree and type of hydrological alteration, an assumption also applied by Bejarano et al. [35]. For the assessment of the hydrological alteration InSTHAN requires two datasets of subdaily flows or water levels to be compared, one representing the perturbed regime and the other the natural regime. The latter may come from the same location as the perturbed one as the preimpact period records or modeled records, or it may come from a comparable river reach.

The impact assessment involves a one-by-one comparison of the whole suite of STCI (record- and period-based STCI involving 366 values per indicator from each day of the averages for n years) from the perturbed and corresponding natural subdaily flow or water level datasets. InSTHAN's output is a suite of short-term impact indicators (STII, record- and period-based STII) obtained through Equation (2). Each impact indicator quantifies the deviation of the perturbed condition (per) from the natural condition (nat) of the corresponding characterization indicator (Equation (2)). \log_{10} is applied to the quotient to avoid excessively high values when the averages of certain indicators in the natural conditions are very low (e.g., indicators related to flow rates of change). Impact indicators can take any positive and negative value and are unitless. Comparisons are not restricted to perturbed and natural series, but other comparisons between series may be made according to user needs.

$$STII_{day(i)} = \text{sign}(STCI_{day(i)}^{nat} - STCI_{day(i)}^{per}) \log_{10} \left[\frac{|STCI_{day(i)}^{nat} - STCI_{day(i)}^{per}|}{\left(\frac{\sum_{i=1}^{i=366} STCI_{day(i)}^{nat}}{366} \right)} + 1 \right] \quad (2)$$

Equation (2): $STII_{day(i)}$: short-term impact indicator for the i th day from 1 to 366 of the year; $\text{sign}(STCI_{day(i)}^{nat} - STCI_{day(i)}^{per})$: sign function for the difference between the short-term characterization indicators for the i th day from 1 to 366 of the year from the natural (nat) and perturbed (per) series; $|STCI_{day(i)}^{nat} - STCI_{day(i)}^{per}|$: absolute value for the difference between the short-term characterization indicators for the i th day from 1 to 366 of the year from the natural and perturbed series and $\sum_{i=1}^{i=366} STCI_{day(i)}^{nat}$: sum of the short-term characterization indicator for the i th day from 1 to 366 of the year from the natural (nat) series.

2.2. InSTHAN's Application and Validation

We were interested in (i) characterizing the short-term flow variability of the Colorado River (USA) along the reach downstream from the Glen Canyon dam before and after its construction (i.e., 1966) and (ii) evaluating the impacts of the dam on this short-term flow regime and, thus, subsequent expected environmental impacts on the fluvial ecosystem. For this aim, and in order to verify InSTHAN's correct operation and demonstrate its advantages, we applied InSTHAN and the Computational Tool for the Characterization of Rapid Fluctuations in Flow and Stage (Sauterleute and Charmasson, 2014; COSH-Tool onwards), which was kindly provided by authors (v2016). We had two original flow (m^3/seg) data series (.xlsx files). The natural series corresponded to hourly flows measured between 1943 and 1951, whereas the perturbed series corresponded to every 15 min flow measured between 2003 and 2011, both at Lees Ferry (9,380,000 gauging station code; data from <https://waterdata.usgs.gov/>). The former file was characterized by one column (flow) without a heading and five decimal places measurements, and the latter was characterized by three columns (date, time, and flow) with their respective headings and two decimal place measurements.

3. Results

3.1. InSTHAN's Characteristics

InSTHAN has been developed in Matlab, and the code is created and executed based on a user's actions within the graphical user interface (GUI). This approach provides convenient access to the most relevant code functions via buttons in the GUI, but translates each user action into executable code that can be captured in a script. The distribution version of the tool is encapsulated into an executable file that does not require a Matlab license for the end user. Moreover, implementing scripting within the GUI enables immediate visualization of results via graph and table-based views of the data. InSTHAN supports the commonly used .xlsx and .txt data files containing flow and/or water level records in columns, measured at any subdaily time interval and provided in any consistent system of units defined by the user. The results are generated into excel files with open code macros to help the user to zoom into long series graphs. Finally, InSTHAN may be deployed on multiple platforms (Windows, Linux and Macintosh), the installation and calculations require little disk space and computing power, respectively, and graphics have satisfactory performance on commonly used processors. Specifically, the required disk space is 27 Mb for computers with Matlab v2018, but 1.56 additional Gb corresponding to the additional libraries distributed with the MCR_R2018a_win64_instaler.exe are necessary when Matlab is not installed. Concerning the computational power, it took four minutes to complete an impact analysis for the selected case study involving the management of records, in a i7, 20 Gb ram PC.

InSTHAN is organized into projects and analyses (Figure 2). A project consists of one to several analyses (e.g., Project 1 and Analyses 1, 2 and 3 in Figure 2). Any calculation of a set of indicators constitutes an analysis, being of two types: characterization analysis, aimed exclusively at characterizing a short-term flow or water level regime (calculation of STCI), and impact analysis, aimed at assessing the alteration of a short-term flow or water level regime (and thus inferring the derived environmental impact; calculation of STII). A folder is generated where specified in the computer to store the projects ("Project 1" directory; Figure 2) where data and all analyses run within the same project are stored, either in an automatically generated folder for the data files ("Excel" subdirectory), for the characterization analyses ("Characterization" subdirectory), or for the impact analyses ("Impact" subdirectory; Figure 2).

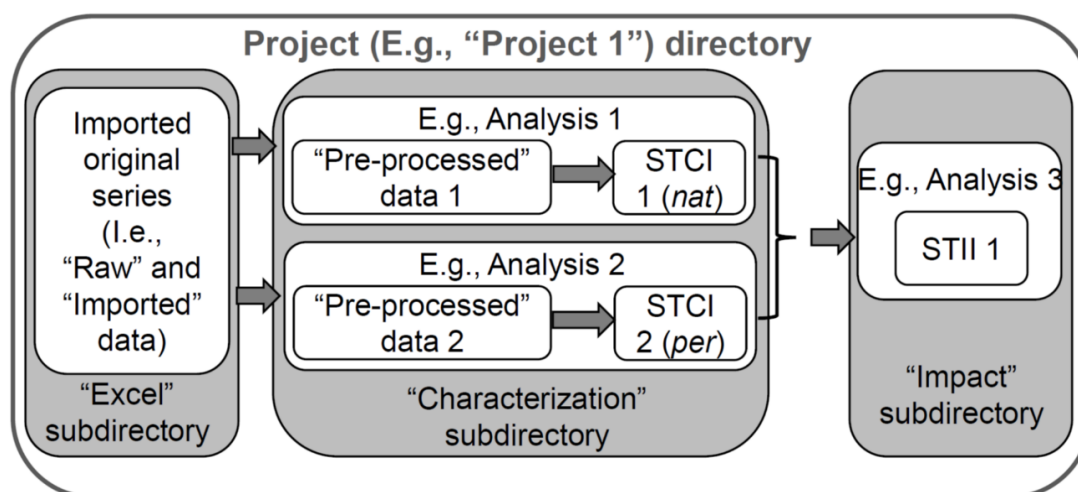


Figure 2. General organization of InSTHAN.

Analyses were linked to short-term data series (Figure 2) characterized by a set of flow or water level records measured (or modeled) at any subdaily time interval and from a specific time period, which was used for the calculation of indicators. Indicators may be calculated on the entire imported original data series (i.e., “Raw” data and “Imported” data), or on a preprocessed data series by changing the analysis period or the time interval between records with InSTHAN (i.e., “Pre-processed” data). Thus, each characterization analysis is linked to a single series, whereas each impact analysis is linked to two series, for example a perturbed (*per*) series and a comparable natural (*nat*) series (Figure 2). The impact assessment may be run (i) on a series of short-term flows or water levels, which can be split in InSTHAN into two independent (sub) series representing the preimpact (natural) and postimpact (perturbed) periods, or (ii) on two independent series representing the perturbed and the natural conditions. In any case, the previous characterization of each perturbed and natural series is necessary for the subsequent evaluation of the impact (Figure 2).

InSTHAN is organized into three modules corresponding to the steps that must be followed to set up and complete an impact assessment analysis, requiring the user to (i) create a project and import the data (Module I: Project management and data import; Supplementary Materials A: Figure S1), (ii) preprocess and analyze the data by calculating the STCI (Module II: Characterization; Supplementary Materials A: Figure S2) and (iii) calculate the STII (Module III: Impact assessment; Supplementary Materials A: Figure S3). Finally, outputs may be displayed in tables and graphs. Details on each module can be found in Supplementary Materials A.

3.2. InSTHAN’s Functionality and Comparison with Other Tools

Both InSTHAN and COSH-Tool were launched from an executable file. Then, the main interface opened and allowed access to analysis of the time series. Both interfaces are simple and require no coding from the user (Table 3). With InSTHAN, two different projects named “ColoradoNat” and “ColoradoPer” were created (Supplementary Materials B: Figure S5). Two different characterization analyses were ran, one for the natural original series (“ColoradoNatCharacterization1”) corresponding to the period before the construction of the dam, and the other for the perturbed original series (“ColoradoPerCharacterization1”), whose outputs were saved into their respective folders within “ColoradoNat” or “ColoradoPer” projects (Supplementary Materials B: Figures S4–S19). While importing the original data series we provided the required information on the series. Then, the two imported data series were preprocessed in order to set the entire available period of data as the characterization analysis period, and to round the flow measurements to two decimal places. The perturbed data series, originally characterized by every 15 min records, was also decimated in InSTHAN to get a measurement every hour.

Table 3. Comparison of the tools used in this article: InSTHAn (v2020) and COSH-Tool (v2016).

Characteristics		InSTHAn	COSH-Tool
General characteristics	Programming language	InSTHAn v2020 is programmed in Matlab, but it does not require a Matlab license and knowledge to deploy and customize output figures	COSH-Tool v2016 is programmed in Matlab and it requires a Matlab license and knowledge to deploy and customize output figures
	Graphical user interface (GUI)	Several windows, friendly user interface	Few windows, friendly user interface
	Languages	User selected between Spanish and English	Default English
Data loading, preparation and organization	File types supported	Excel and text files	Excel
	Number of variables per file	Up to four	One
	Data resolution	Intraday. It allows to change the time interval of records	Intraday. It does not allow to change the time interval of records
	Data units	User defined	User selected among options (stage (m), flow (m ³ /s), unidentified)
	Navigation in the PC	Yes	No
	Organization of analyses	Hierarchical organization in projects and analyses, which may be open, consulted and modified anytime	No hierarchical organization. Analyses cannot be open, consulted and modified by the user
Data preprocessing	Preprocessing options	Selection of subperiods of analysis, data decimation (grouping records in larger time intervals), and data filtering (rounding the measurement figures)	Selection of subperiods of analysis, deletion of outliers, and data smoothing (moving average). No decimation (grouping records in larger time intervals) and data filtering (rounding the measurement figures)
Data analysis	Characterization	Based on patterns assigned to records and periods (within-day portions of time of similar pattern among records). They can be: rise, fall, stability change and reversals. No user requirements for patterns identification	Based on peaking events. They can be: rapid increase and rapid decrease. Peaking events identification is conditional on the provision of several figures by the user (the inferior and superior percentiles of the rate of change, a minimum duration for a peak, the magnitude threshold to merge peaks and the minimum duration between two consecutive peaks)
		Through metrics and statistics relating to the major flow components (i.e., magnitude, frequency, duration and rate of change). Deepening the duration of patterns. Information on stability and change patterns. See Table 2 for details (named STCI)	Through metrics and statistics relating to the major flow components (i.e., magnitude, frequency, duration and rate of change). No deepening the duration of peaking events. No information on stability and change patterns. See Table 1 in Sauterleute and Charmasson [21] for details
Outputs	Impact	Through comparisons of characterization metrics (STCI) from natural and perturbed series (named STII)	No
	Outputs format	Comprehensive tables and many figures in excel. Easy customization of figures through Excel	Simplified tables in excel. Many figures deployed in Matlab. Customization of figures and access to the data represented by the figures through Matlab
	Outputs scale	It captures each day's subdaily patterns of the series, from which the user may derive longer-scale patterns	It captures daylight, monthly, seasonal and annual patterns

The natural and perturbed series were also loaded and prepared with COSH-Tool. Apart from small differences between the tools related to restrictions on the navigation in the PC, or on allowed variables, units and languages (Table 3), a notable difference of COSH-Tool is the non-organization of the outputs within projects or/and analyses where they may be easily found and consulted (Table 3). With a purpose similar to rounding in InSTHAN, smoothing was required by COSH-Tool at this stage. Smoothing, however, depends on a “smoothing factor” set by the user, which must be within a range of figures used during testing of the tool. Unlike InSTHAN, COSH-Tool is unable to modify the record interval of the input series, so the original every 15 min, perturbed series had to be turned into hourly time step series before loading to ensure that both natural and perturbed series had similar record intervals for later comparisons. Finally, for both natural and perturbed original series patterns were assigned to records (*R*) and periods (*P*) by InSTHAN (i.e., fall, rise, stability, change and reversal), but peaking events (i.e., rapid increases and decreases) were identified by COSH-Tool (Figure 1). Whereas the detection of such patterns in InSTHAN is based on differences between each previous and following rounded record and does not depend on predefined values, the detection of peaking events in COSH-Tool is conditional on the provision of several figures by the user, such as the inferior and superior percentiles of the rate of change, a minimum duration for a peak, the magnitude threshold to merge peaks, and the minimum duration between two consecutive peaks (Table 3). Since the subsequent characterization of the series is based on the patterns and peaking events previously identified by InSTHAN and COST-Tool, respectively, setting different figures in COSH-Tool may result in variations of the peaking events of a series, ultimately affecting its characterization (Figure 1). For the perturbed case, the whole flow series was split into many periods of rise and fall, and reversals and changes by InSTHAN (Figure 1). However, for the same series, the rapid increases and decreases were confined to the flow records that met the user-set (recommended by the users’ manual) parameters (cf. above) by COSH-Tool (Figure 1). For the natural flow series, significantly more patterns through years were detected by InSTHAN compared to the almost non-existent peaking events found by COSH-Tool (Figure 1).

After data series loading and preparation, we required InSTHAN and COSH-Tool to characterize the natural and perturbed subdaily flow regimes. The records (*R*) and periods (*P*) previously assigned to different patterns were characterized by InSTHAN, whereas characterization of the identified peaking events was done by COSH-Tool. In both tools, characterization is done through metrics and statistics relating to the major flow components (i.e., magnitude, frequency, duration and rate of change; Table 3). However, a more thorough characterization representing all facets of the subdaily variation is achieved with InSTHAN, which goes into greater depth in duration metrics and provides information on periods of stability and reversals and changes (Table 3). Whereas InSTHAN’s metrics (STCI) capture each day’s subdaily patterns of the series, from which the user may derive longer-scale patterns through averaging the excel outputs, metrics from COSH-Tool characterize monthly, seasonal and annual patterns, which are displayed in figures (Table 3). Only a brief summary of the outputs for the whole analyzed period is provided in an excel template by COSH-Tool. Unlike InSTHAN, COSH-Tool also provides daylight patterns. Characterization metrics representative of each flow component (frequency, duration, magnitude and rate of change) have been chosen from each tool for Figure 3 (further outputs from InSTHAN can be consulted in Supplementary Materials B and in Alonso et al. [31] and Bejarano et al. [32]).

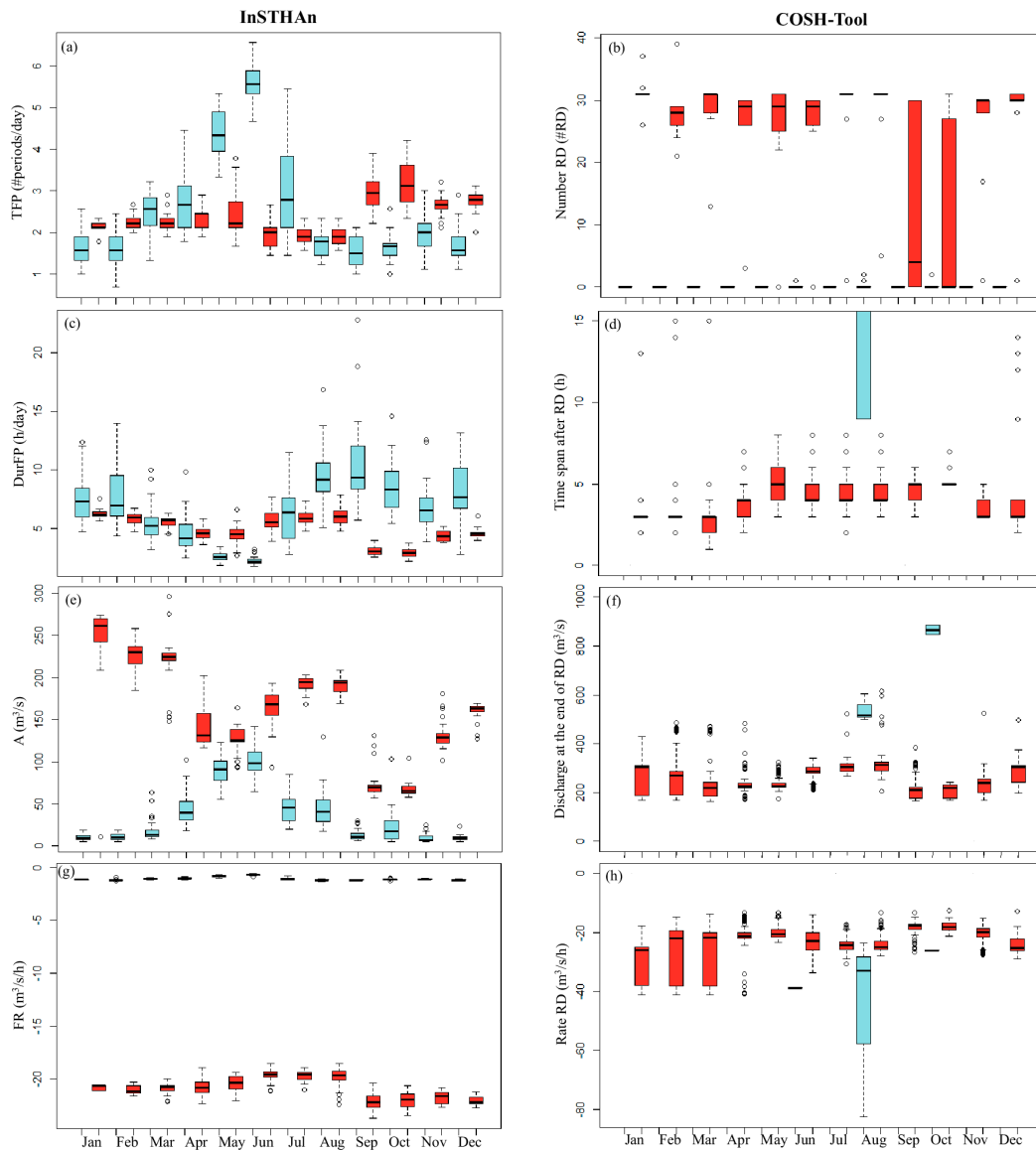


Figure 3. Box-and-whisker plots for selected outputs from the characterization analyses ran in InSTHAN and COSH-Tool for the pre- and post-dam (Glen Canyon dam) flow series (1943–1951 hourly flows, and 2003–2011 every-15 min flows, respectively) along the downstream reach of the Colorado River. *y*-axes represent the months in pre- (natural) and post-dam (perturbed) conditions, colored in blue and red, respectively. Black lines in the middle of the boxes are the median values for each group. The vertical size of the boxes is the interquartile range (IQR). The whiskers represent the minimum and maximum values that do not exceed $1.5 \times$ IQR. The points are outliers. *x*-axes represent the characterization metrics related to frequency, duration, magnitude and rates of change provided by InSTHAN (i.e., short-term characterization indicators (STCI); **a,c,e,g**) and COSH-Tool (**b,d,f,h**). For InSTHAN, selected metrics are: **(a)** monthly average number of fall periods per day for the whole flow series, **(c)** monthly average duration of fall periods per day for the whole flow series, **(e)** monthly average amplitude per day for the whole series and **(g)** monthly average rate of flow decrease per day for the whole series. For COSH-Tool, the selected metrics are: **(b)** total number of rapid decreases per month for the whole series, **(d)** time span after rapid decreases per month for the whole series (not shown were three values in June, August and October for the natural period, which were higher than 15 h), **(f)** discharge after rapid decreases per month for the whole series (not shown was one value in June for the natural period, which was higher than $1000 \text{ m}^3/\text{s}$) and **(h)** rate of flow decrease of rapid decreases per month for the whole series.

Both InSTHAN and COSH-Tool were able to capture the hydropeaking derived from the operation of the Glen Canyon dam in the perturbed flow series. In general, from both tools the user can derive that hydropeaking is associated to significantly frequent and short fall (and rise) periods (InSTHAN) or rapid decreases (and increases; COSH-Tool); fast hourly flow changes (highlighted by both tools) and high within-day flow amplitude (InSTHAN) and discharge (COSH-Tool; Figure 3). On average, InSTHAN identified three, 5 h fall periods per day during the whole year for regulated conditions (Figure 3). Other metrics (not shown) were consistent with these figures; the more frequent the fall (and rise) periods, the more frequent the flow changes and reversals, and the more frequent and shorter the stability periods. On average, COSH-Tool identified 25 rapid decreases per month for regulated conditions and described short time spans after rapid decreases (5 h on average) for regulated conditions (Figure 3). For the series subjected to hydropeaking, InSTHAN showed that the average daily amplitude was $162 \text{ m}^3/\text{s}$ and the flow receded at a rate of $(-)$ $21 \text{ m}^3/\text{s}/\text{h}$, whereas COSH-Tool showed an average discharge at the end of a decrease of $263 \text{ m}^3/\text{s}$ and of rate of flow decrease per month of $(-)$ $24 \text{ m}^3/\text{s}/\text{h}$ (Figure 3). Conversely, the characterization of the natural series did vary significantly between the tools. Whereas the patterns of the flows used by InSTHAN for the characterization are also found in the series regardless of whether it is regulated or not, the peaking events used by COSH-Tool are restricted to artificial changes of the series, such as hydropeaking, and linked to exceptional natural peaking events (Figure 3). Consequently, hardly any peaking events were found by COSH-Tool throughout the natural flow series and, thus, most metrics were not applicable or equaled zero (Figure 3). The values for the metrics mentioned above obtained by applying InSTHAN to the natural series were in general (except for the spring values) significantly lower than the values from the perturbed series. Average values were as follows: four, 3 h fall periods per day and two, 8 h fall periods per day for the spring and the remaining seasons, respectively; a daily amplitude of $79 \text{ m}^3/\text{s}$ during the flooding season and $21 \text{ m}^3/\text{s}$ for the rest of the year and an hourly flow rate of $1 \text{ m}^3/\text{s}/\text{h}$ (Figure 3).

In InSTHAN we ran an impact analysis named “ColoradoImpact1”, whose outputs were saved into its corresponding folder within one of the existing projects (the project “ColoradoNat” in our case; Supplementary Materials B: Figures S20–S25). For the impact analysis we indicated the characterization files to compare natural and perturbed (i.e., “ColoradoNatCharacterization1” and “ColoradoPerCharacterization1”) from the InSTHAN dropdown menu and the deviation from the naturalness of each metric for each day of an average year was calculated. Impact assessment is not available in COSH-Tool (Table 3). Described changes on each STCI are summarized by their respective STII, which evidence both the magnitude and the direction of the impact (a selection of STII is shown in Figure 4). On the one hand, the very positive STII values highlight the significant increase of the within-day flow amplitude and rates of change resulting from hydropeaking (Figure 4). On the other, the close-to-zero, positive and close-to-zero, negative STII values highlight the slight increase or decrease of the frequency and duration of the fall periods with regulation, respectively; the pattern is only unfulfilled during the flooding period (Figure 4).

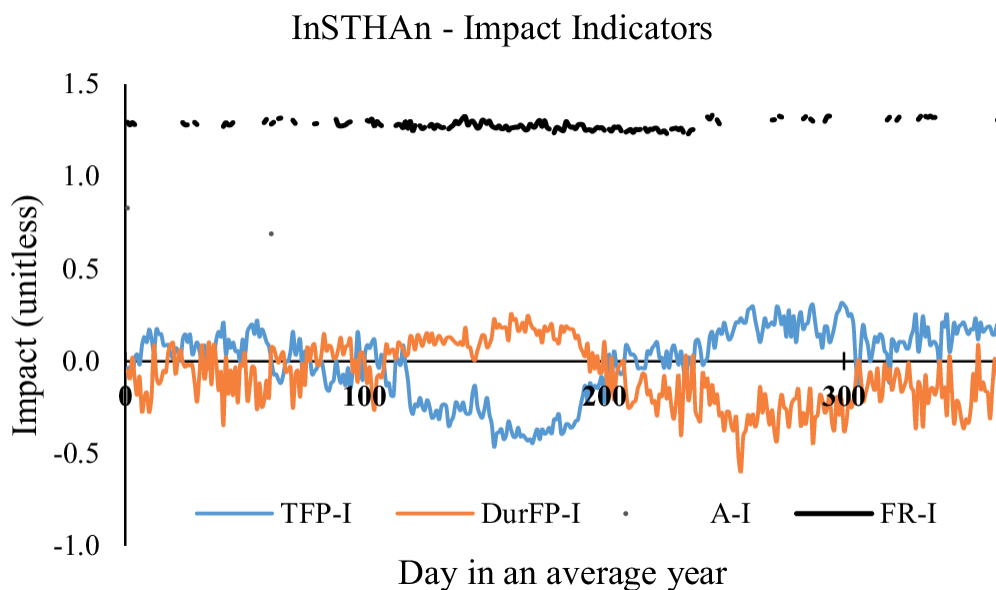


Figure 4. Outputs from the impact analyses ran in InSTHAN for the above mentioned characterization indicators (short-term impact indicators [STII]; -I denotes the impact on each indicator). Values around 0 mean a slight impact.

4. Discussion and Conclusions

4.1. Applicability

InSTHAN assists both scientists and river managers in describing and evaluating the naturalness of short-term flow/water level regimes, thus, eventually facilitating the understanding of the potential environmental impacts of the alterations of these regimes. Results from the application of InSTHAN to the analysis of the short-term flow variation in the Colorado River denote important modifications of certain key hydrological parameters at the subdaily scale due to the operation of the Glen Canyon dam. These would, otherwise, have gone unnoticed with other tools based on daily or larger time scale flow records. The derived consequences of these changes for the fluvial ecosystem may be severe. Particularly, significantly higher amplitudes of subdaily flows due to a regulation increase of the everyday wetted area, which may remove or move upwards on riparian areas plant species less tolerant to flooding while triggering the development of aquatic or amphibian species. Such consequences were described by Bejarano et al. [16] in rivers with hydropeaking from Northern Sweden, where *Betula pubescens* survival decreased significantly whereas *Salix* and *Carex* species were favored. Additionally, the significantly faster flow rates of change may result in fish/egg stranding, macroinvertebrate drift and obstruction of germination. For example, Casas-Mulet et al. [36] related the higher mortality of *Salmo salar* eggs in a river in central Norway to rapid dewatering, and Schülting et al. [37] observed macroinvertebrate drift proportions peaked during the up-ramping phase of water in an experimental flume. Although altered to a lesser extent, the more frequent and shorter inundations within a day may also cause scouring and burial, and soil surface clogging, damage or removal of sessile organisms or life stages and habitat deterioration and loss, which was already reported by Vanzo et al. [7].

Although based on different characterization units (patterns or peaking events), both InSTHAN and COSH-Tool were reliable for the characterization of short-term scale flow and water level series. The single characterization of the short-term natural and regulated flow regimes is valuable as it increases scientific knowledge on geographic patterns of hydrological variability [38,39], and helps to understand the influence of these patterns on biological communities and ecological processes [40]. InSTHAN's added contribution lies in its ability to quantitatively assess the short-term hydrological alteration by comparing identified patterns in natural and regulated conditions. Consequently, and unlike COSH-Tool, InSTHAN brings water managers and scientists closer to the potential ecological

consequences of the hydrological alteration, and to whether consequences may be irreversible (when exceeding the ecosystem's thresholds), ultimately helping to determine the resistance and resilience of the river [41]. This knowledge is key for guiding any river management strategies [42], the assessment of its ecological status [34,43], prioritizing conservation efforts [44] and setting and measuring progress toward conservation or restoration goals [45]. Particularly, InSTHAN's results from the analyzed series would be useful when determining operational rules at the Glen Canyon plant and/or in-situ compensation measures aimed at harmonizing hydropower production and ecological integrity of the river [46]. Whatever the purpose, InSTHAN should be used in combination with other tools focused on longer time resolutions such as the IHA [34], in order to guarantee the comprehensiveness of the analyses by accounting for hydrological attributes at all time scales [47].

4.2. Merits and Limitations of InSTHAN in Relation to Other Tools

The appeal of InSTHAN is that it facilitates the analysis of long data series, which would otherwise be tedious. It offers several advantages and improvements over its peers. It allows different languages, reads widely used files of data from any source, records at any subdaily time scale and characterizes by a wide range of date styles and data units, and up to four variables in the same sheet can be imported; options that are more limited in existing tools. Additionally, InSTHAN provides a set of descriptive subdaily hydrological indicators comprehensive enough to account for the most ecologically determinant hydrological attributes [32], overcoming the limitations of other tools in duration metrics. Although it has been specially designed for flow and water level datasets, as included indicators make sense in the context of the field of stream hydrology, the user may consider it appropriate for other variable types recorded at similar short-term resolution, e.g., water temperature or water dissolved gasses in order to analyze the phenomena of thermopeaking [48] and saturopeaking [6], respectively. All these variables are usually affected by hydropower production, which has been the focus of this manuscript, but InSTHAN could be useful also in cases when flows are manipulated by dams with other purposes than electric power generation but also involving the alteration of the short-term flows.

An interesting novelty is that InSTHAN allows adaptive analyses by modifying the analysis periods (i.e., subperiods), the recording time intervals (i.e., to longer subdaily time steps) and the accuracy to detect subdaily patterns (i.e., thresholds from which a fluctuation is considered). The latter is crucial to avoid unreal fluctuations led by the influence of the accuracy of the measuring device or the model, or simply measurement or modeling errors [30], and which is lacking in existing tools. Finally, no tools to date enable the assessment of the alteration of short-term regimes (Table 1). Specifically, COSH-Tool founds the characterization of subdaily regimes on peaking events (to some extent similar to the so-called pulses by other authors) previously identified by the user based on subjectively defined thresholds (e.g., [4,21,28,30]; Table 1). As our results show, the use of peaking events as characterization units prevents the characterization of natural (or slightly affected) series usually lacking such events. This is not minor, as impact can only be assessed by comparing natural and perturbed series pairs. Characterization in InSTHAN, however, is based on patterns ultimately describing the records of the series. This, first, guarantees objectivity in the identification process of subdaily patterns, which, secondly, can be performed for any series regardless of the degree of alteration.

From a practical perspective, InSTHAN has been designed for a wide audience with different backgrounds and expertise. Although the decision-maker is often a water resources manager within a mandated organization, stakeholder participation, including water abstractors, wildlife campaigners and local community representatives, play a role in influencing decisions [49]. Unfortunately, reaching agreement is hindered by such a range of interested parties with usually conflicting goals, which can rely on InSTHAN outputs to set balanced thresholds. For this aim, InSTHAN is an easy installation tool, which requires little computer memory and optimizes the calculation time. The friendly windows within the GUI and clear results displayed through tables and graphs, which can be read and managed from Excel files, help to make the tool easy to use even for inexperienced users. Furthermore, it can be customized to change the language, units,

and add/remove/zoom into graphs. Unfortunately, for the authors' experience, the navigation through COSH-Tool and management of results was not as straightforward and intuitive.

With regards to the limitations of InSTHAN, we point out again that derived environmental impacts of short-term hydrological alterations are not directly provided by the tool but can be derived from the already understood ecological implications of the calculated hydrological indicators. Consequently, understanding of the ecological impacts from the outputs may require additional expertise and this may vary according to specific species, conservation objectives and site characteristics. Further research should address this issue. Another important limitation of InSTHAN derives from the requirements for the input data. Although InSTHAN may be run on daily (or longer intervals) data, results may not make sense at such time scales as indicators are focused exclusively on capturing subdaily patterns. Results should be analyzed with caution if subdaily records are few. In such cases, other tools could be more suitable (e.g., [34]). Further, for the case of hydrological datasets, measuring (especially in free-flowing rivers) and modeling at such fine resolution are still uncommon. This particularly affects the impact assessment module, which is dependent on free-flowing series. In the absence of data from free-flowing rivers, the solution would involve the restitution of the free-flowing regime at the study location. To accomplish this, at least one (representative) year of subdaily flows or water levels should be recorded at a comparable location (for example by using pressure-transducer loggers), which would provide the natural subdaily variability applied to model a longer period based on commonly available daily records (registered or modeled). In rivers with high interannual flow variability, more than one year of registered subdaily data would be desirable. A last restriction on the input data is that, with any subdaily registering interval allowed, this interval must remain constant throughout the whole study period. Finally, in the spirit of InSTHAN being a user-friendly tool that attracts a wide range of users, those who are more experienced may not like that actions are restricted to windows and cannot be ordered through commands.

4.3. Future Versions

We are working on completing existent modules and introducing new modules of InSTHAN. The modular structure and the tool architecture allow the inclusion of new modules that may extend the tool functions in future versions. Within the characterization and impact modules, new indicators will be added in future versions such as measures of central tendency and dispersion for the indicators. In addition, subdaily patterns will be summarized at other time spans apart from the daily basis (i.e., currently, indicators take an average value for each day). For example, subdaily flow fluctuations caused by hydropeaking along northern regions are higher during daytime, workdays or cold seasons following electricity demands [50]. Detecting these variations in subdaily flow patterns is key when planning strategies for sustainable hydropower management. In this regard, COSH-Tool already distinguishes between daytime and nighttime analysis. Limits on hydropower production could focus on situations when restrictions may result in great ecological gains but small economic losses. A module for the categorization of data series according to their subdaily patterns or impact will be built. We believe that it may facilitate management as similar management rules may be prescribed to all series pertaining to the same group [32]. Finally, extra ecological and economic modules, which provide the ecological and economic consequences of the already identified and quantified hydrological changes would round off the current version of the proposed tool. InSTHAN should be tested with other data series and improved accordingly. For this to be realized, our purpose is to make it generally accessible as soon as the patent is obtained by downloading it for free from a webpage with user registration as the only requirement. A user manual will be also available on the same webpage. The user may share his/her experience when using the tool, inform of the degree of satisfaction with it and ask doubts or suggest changes that could be included in future versions.

4.4. Conclusions

We introduced the new tool InSTHAN: indicators of short-term hydrological alteration. InSTHAN allows the user to (i) summarize multiple, long series of subdaily flow or stage data into a manageable set of ecologically meaningful metrics (i.e., characterization), (ii) qualify and quantify the deviation of each series from the unaltered state to assess the hydrological alteration and its potential environmental impact and (iii) display both the short-term flow or stage pattern and its impact by using tables and graphs. The name informs on its ultimate purpose and time scale of the target regime, whereas the pronunciation of the acronym refers to the required recording interval of the input data (i.e., instant records). InSTHAN represents an advance compared to existing tools. In the characterization stage, it guarantees objectivity in the identification of subdaily patterns from any (natural or altered) series, and provides a comprehensive set of ecologically meaningful hydrological indicators. In the impact stage, it enables the assessment of the alteration of short-term regimes. Finally, in terms of its functionality, it is characterized by the flexibility in the analyses (analysis periods, recording time intervals and accuracies to detect subdaily patterns) and in the supported languages, files and datasets properties (date styles, records time intervals and data units), and it is a friendly tool because its straightforward installation and use (windows within the GUI and clear display of results). InSTHAN responds to real-world needs in the fields of science and technology, and ultimately of society. By facilitating complex data management, it promotes the development of scientific studies on the short-term variability of river flows and levels—natural and altered by anthropogenic actions—underlying key ecological processes in rivers. By providing comprehensive and objective information on short-term stream flows and levels, this tool solves conflicting user perspectives and, hence, supports the sustainable integrated assessment and management of river systems. InSTHAN is particularly useful in the environmental management of rivers used for hydropower production, as it will assist in achieving the priority goal of maximizing hydroelectricity production while minimizing environmental losses.

Supplementary Materials: The following are available online at <http://www.mdpi.com/2073-4441/12/10/2913/s1>, Figure S1. Project management and data import module (InSTHAN's Module I), Figure S2. Characterization module (InSTHAN's Module II), Figure S3. Impact assessment module (InSTHAN's Module III), Figure S4. Start a new or load an existing project, Figure S5. Import the original data, Figure S6. Export "Raw" data and "Imported" data. Example from the post-dam flows, Figure S7. Export "Raw" data and "Imported" data, Figure S8. See "Imported" data. Example from the post-dam flows, Figure S9. Create a new or load an existing Characterization analysis, Figure S10. Select the Characterization analysis that we want to load from a list, Figure S11. Create and run a new Characterization analysis, Figure S12. Export Characterization analysis: main menu. Example from the post-dam flows, Figure S13. Export Characterization analysis: main results, Figure S14. Export Characterization analysis: extra results, Figure S15. See "Pre-processed" data. Example from the post-dam flows, Figure S16. See "RP Patterns" file: table sheet. Example from the post-dam flows, Figure S17. See "RP Patterns" file: graph sheet. Example from the post-dam flows (January, 2003 is represented), Figure S18. See "STCI 366" file: table sheet. Example from the post-dam flows, Figure S19. See "STCI 366" file: graph sheet. Example from the post-dam flows (The entire year values for two indicators are shown), Figure S20. Create a new or load an existing Impact analysis, Figure S21. Create and run a new Impact analysis, Figure S22. Export Impact analysis: main menu, Figure S23. Export Impact analysis, Figure S24. See "STII 366" file: table sheet, Figure S25. See "STII 366" file: graph sheet (The entire year values for two indicators are represented).

Author Contributions: Conceptualization, M.D.B.; methodology, J.H.G.-P. and A.S.-W.; investigation and formal analysis, M.D.B., J.H.G.-P. and A.S.-W.; resources and data curation, J.H.G.-P.; writing—original draft preparation, M.D.B.; writing—review and editing, C.N. and L.G.; visualization and supervision, C.N. and L.G.; funding acquisition, M.D.B. and A.S.-W. All authors have read and agreed to the published version of the manuscript.

Funding: This manuscript was supported by funding from: the Spanish Ministry of Science and Innovation (RIHEL; Ref. PID2019-111252RA-I00 CTA and SECA-SRH; Ref. PID2019-105852RA-I00); and Universidad Politécnica de Madrid (Programa Propio: Ayudas a Proyectos de I+D de Investigadores Posdoctorales) and Comunidad de Madrid (Convenio Plurianual con la Universidad Politécnica de Madrid) (Ref. APOYO-JOVENES-PHZK KU-148- SSPVMP).

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Poff, N.L.; Allan, J.D.; Bain, M.B.; Karr, J.R.; Prestegard, K.L.; Richter, B.D.; Sparks, R.E.; Stromberg, J.C. The natural flow regime. *BioScience* **1997**, *47*, 769–784. [[CrossRef](#)]
2. Poff, N.L.; Zimmerman, J.K. Ecological responses to altered flow regimes: A literature review to inform the science and management of environmental flows. *Freshw. Biol.* **2010**, *55*, 194–205. [[CrossRef](#)]
3. Biggs, B.J.; Nikora, V.I.; Snelder, T.H. Linking scales of flow variability to lotic ecosystem structure and function. *River Res. Appl.* **2005**, *21*, 283–298. [[CrossRef](#)]
4. Archer, D.; Newson, M. The use of indices of flow variability in assessing the hydrological and instream habitat impacts of upland afforestation and drainage. *J. Hydrol.* **2002**, *268*, 244–258. [[CrossRef](#)]
5. Eng, K.; Carlisle, D.M.; Wolock, D.M.; Falcone, J.A. Predicting the likelihood of altered streamflows at ungauged rivers across the conterminous United States. *River Res. Appl.* **2013**, *29*, 781–791. [[CrossRef](#)]
6. Pulg, U.; Vollset, K.W.; Velle, G.; Stranzl, S. First observations of saturation peaking: Characteristics and implications. *Sci. Total Environ.* **2016**, *573*, 1615–1621. [[CrossRef](#)] [[PubMed](#)]
7. Vanzo, D.; Zolezzi, G.; Siviglia, A. Eco-hydraulic modelling of the interactions between hydropeaking and river morphology. *Ecohydrology* **2015**, *9*, 421–437. [[CrossRef](#)]
8. Bejarano, M.D.; Jansson, R.; Nilsson, C. The effects of hydropeaking on riverine plants: A review. *Biol. Rev.* **2018**, *93*, 658–673. [[CrossRef](#)]
9. Casas-Mulet, R.; Alfredsen, K.; Boissy, T.; Sundt, H.; Rütther, N. Performance of a one-dimensional hydraulic model for the calculation of stranding areas in hydropeaking rivers. *River Res. Appl.* **2015**, *31*, 143–155. [[CrossRef](#)]
10. Boavida, I.; Harby, A.; Clarke, K.D.; Heggenes, J. Move or stay: Habitat use and movements by Atlantic salmon parr (*Salmo salar*) during induced rapid flow variations. *Hydrobiologia* **2017**, *785*, 261–275. [[CrossRef](#)]
11. Flodmark, L.E.W.; Vøllestad, L.A.; Forseth, T. Performance of juvenile brown trout exposed to fluctuating water level and temperature. *J. Fish Biol.* **2004**, *65*, 460–470. [[CrossRef](#)]
12. Nagrodski, A.; Raby, G.D.; Hasler, C.T.; Taylor, M.K.; Cooke, S.J. Fish stranding in freshwater systems: Sources, consequences, and mitigation. *J. Environ. Manag.* **2012**, *103*, 133–141. [[CrossRef](#)] [[PubMed](#)]
13. Holzapfel, P.; Leitner, P.; Habersack, H.; Graf, W.; Hauer, C. Evaluation of hydropeaking impacts on the food web in alpine streams based on modelling of fish-and macroinvertebrate habitats. *Sci. Total Environ.* **2017**, *575*, 1489–1502. [[CrossRef](#)]
14. Leitner, P.; Hauer, C.; Graf, W. Habitat use and tolerance levels of macroinvertebrates concerning hydraulic stress in hydropeaking rivers—A case study at the Ziller River in Austria. *Sci. Total Environ.* **2017**, *575*, 112–118. [[CrossRef](#)]
15. Gorla, L.; Signarbieux, C.; Turberg, P.; Buttler, A.; Perona, P. Effects of hydropeaking waves' offsets on growth performances of juvenile *Salix* species. *Ecol. Eng.* **2015**, *77*, 297–306. [[CrossRef](#)]
16. Bejarano, M.D.; Sordo-Ward, A.; Alonso, C.; Jansson, R.; Nilsson, C. Hydropeaking affects germination and establishment of riverbank vegetation. *Ecol. Appl.* **2020**, *30*, e02076. [[CrossRef](#)]
17. Schmutz, S.; Bakken, T.H.; Friedrich, T.; Greimel, F.; Harby, A.; Jungwirth, M.; Melcher, A.; Unfer, G.; Zeiringer, B. Response of fish communities to hydrological and morphological alterations in hydropeaking rivers of Austria. *River Res. Appl.* **2015**, *31*, 919–930. [[CrossRef](#)]
18. Jackson, D.C.; Brown, A.V.; Davies, W.D. Zooplankton transport and diel drift in the Jordan dam tailwater during a minimum flow regime. *Rivers* **1991**, *2*, 190–197.
19. Zarfl, C.; Lumsdon, A.E.; Berlekamp, J.; Tydecks, L.; Tockner, K. A global boom in hydropower dam construction. *Aquat. Sci.* **2015**, *77*, 161–170. [[CrossRef](#)]
20. Haas, N.A.; O'Connor, B.L.; Hayse, J.W.; Bevelhimer, M.S.; Endreny, T.A. Analysis of daily peaking and run-of-river operations with flow variability metrics, considering subdaily to seasonal time scales. *J. Am. Water Resour. Assoc.* **2014**, *50*, 1622–1640. [[CrossRef](#)]
21. Sauterleute, J.F.; Charmasson, J. A computational tool for the characterisation of rapid fluctuations in flow and stage in rivers caused by hydropeaking. *Environ. Model. Softw.* **2014**, *55*, 266–278. [[CrossRef](#)]
22. Topping, D.J.; Schmidt, J.C.; Vierra, L.E. *Computation and Analysis of the Instantaneous-Discharge Record for the Colorado River at Lees Ferry, Arizona, 8 May 1921, through 30 September 2000*; USGS: Reston, FL, USA, 2003.
23. White, M.A.; Schmidt, J.C.; Topping, D.J. Application of wavelet analysis for monitoring the hydrologic effects of dam operation: Glen Canyon Dam and the Colorado River at Lees Ferry, Arizona. *River Res. Appl.* **2005**, *21*, 551–565. [[CrossRef](#)]

24. Meile, T.; Boillat, J.L.; Schleiss, A.J. Hydropeaking indicators for characterization of the Upper-Rhone River in Switzerland. *Aquat. Sci.* **2011**, *73*, 171–182. [[CrossRef](#)]
25. Zimmerman, J.K.H.; Letcher, B.H.; Nislow, K.H.; Lutz, K.A.; Magilligan, F.J. Determining the effects of dams on subdaily variation in river flows at a wholebasin scale. *River Res. Appl.* **2010**, *26*, 1246–1260. [[CrossRef](#)]
26. Bevelhimer, M.S.; McManamay, R.A.; O'Connor, B. Characterizing sub-daily flow regimes: Implications of hydrologic resolution on ecohydrology studies. *River Res. Appl.* **2015**, *31*, 867–879. [[CrossRef](#)]
27. Carolli, M.; Vanzo, D.; Siviglia, A.; Zolezzi, G.; Bruno, M.C.; Alfredsen, K. A simple procedure for the assessment of hydropeaking flow alterations applied to several European streams. *Aquat. Sci.* **2015**, *77*, 639–653. [[CrossRef](#)]
28. Chen, Q.; Zhang, X.; Chen, Y.; Li, Q.; Qiu, L.; Liu, M. Downstream effects of a hydropeaking dam on ecohydrological conditions at subdaily to monthly time scales. *Ecol. Eng.* **2015**, *77*, 40–50. [[CrossRef](#)]
29. Barbačić, D.; Kuspilić, N. Indicators of sub-daily hydrological alterations. *Teh. Vjesn.* **2015**, *22*, 1345–1352.
30. Greimel, F.; Zeiringer, B.; Höller, N.; Grün, B.; Godina, R.; Schmutz, S. A method to detect and characterize sub-daily flow fluctuations. *Hydrol. Process.* **2016**, *30*, 2063–2078. [[CrossRef](#)]
31. Alonso, C.; Román, A.; Bejarano, M.D.; García de Jalón, D.G.; Carolli, M. A graphical approach to characterize sub-daily flow regimes and evaluate its alterations due to hydropeaking. *Sci. Total Environ.* **2017**, *574*, 532–543. [[CrossRef](#)]
32. Bejarano, M.D.; Sordo-Ward, A.; Alonso, C.; Nilsson, C. Characterizing effects of hydropower plants on sub-daily flow regimes. *J. Hydrol.* **2017**, *550*, 186–200. [[CrossRef](#)]
33. Ashraf, F.B.; Haghighi, A.T.; Riml, J.; Alfredsen, K.; Koskela, J.J.; Kløve, B.; Marttila, H. Changes in short term river flow regulation and hydropeaking in Nordic rivers. *Sci. Rep.* **2018**, *8*, 17232. [[CrossRef](#)]
34. Richter, B.D.; Baumgartner, J.V.; Powell, J.; Braun, D.P. A method for assessing hydrologic alteration within ecosystems. *Conserv. Biol.* **1996**, *10*, 1163–1174. [[CrossRef](#)]
35. Bejarano, M.D.; Sordo-Ward, A.; Gabriel-Martin, I.; Garrote, L. Tradeoff between economic and environmental costs and benefits of hydropower production at run-of-river-diversion schemes under different environmental flows scenarios. *J. Hydrol.* **2019**, *572*, 790–804. [[CrossRef](#)]
36. Casas-Mulet, R.; Saltveit, S.J.; Alfredsen, K. The survival of Atlantic salmon (*Salmo salar*) eggs during dewatering in a river subjected to hydropeaking. *River Res. Appl.* **2015**, *31*, 433–446. [[CrossRef](#)]
37. Schülting, L.; Feld, C.K.; Zeiringer, B.; Huđek, H.; Graf, W. Macroinvertebrate drift response to hydropeaking: An experimental approach to assess the effect of varying ramping velocities. *Ecohydrology* **2019**, *12*, e2032. [[CrossRef](#)]
38. Poff, N.L.; Olden, J.D.; Pepin, D.M.; Bledsoe, B.P. Placing global stream flow variability in geographic and geomorphic contexts. *River Res. Appl.* **2006**, *22*, 149–166. [[CrossRef](#)]
39. McManamay, R.A.; Orth, D.J.; Dolloff, C.A.; Frimpong, E.A. A regional classification of unregulated stream flows: Spatial resolution and hierarchical frameworks. *River Res. Appl.* **2012**, *28*, 1019–1033. [[CrossRef](#)]
40. Puckridge, J.T.; Sheldon, F.; Walker, K.F.; Boulton, A.J. Flow variability and the ecology of large rivers. *Mar. Freshw. Res.* **1998**, *49*, 55–72. [[CrossRef](#)]
41. McCluney, K.E.; Poff, N.L.; Palmer, M.A.; Thorp, J.H.; Poole, G.C.; Williams, B.S.; Williams, M.R.; Baron, J.S. Riverine macrosystems ecology: Sensitivity, resistance, and resilience of whole river basins with human alterations. *Front. Ecol. Environ.* **2014**, *12*, 48–58. [[CrossRef](#)]
42. Arthington, A.H.; Kennen, J.G.; Stein, E.D.; Webb, J.A. Recent Advances in Environmental Flows Science and water management—Innovation in the Anthropocene. *Freshw. Biol.* **2018**, *63*, 1022–1034. [[CrossRef](#)]
43. Dudgeon, D.; Arthington, A.H.; Gessner, M.O.; Kawabata, Z.I.; Knowler, D.J.; Lévêque, C.; Naiman, R.J.; Prieur-Richard, A.H.; Soto, D.; Stiassny, M.L.J.; et al. Freshwater biodiversity: Importance, threats, status and conservation challenges. *Biol. Rev.* **2006**, *81*, 163–182. [[CrossRef](#)] [[PubMed](#)]
44. Snelder, T.H.; Dey, K.L.; Leathwick, J.R. A procedure for making optimal selection of input variables for multivariate environmental classifications. *Conserv. Biol.* **2007**, *21*, 365–375. [[CrossRef](#)] [[PubMed](#)]
45. Palmer, M.A.; Bernhardt, E.S.; Allan, J.D.; Lake, P.S.; Alexander, G.; Brooks, S.; Carr, J.; Clayton, S.; Dahm, C.N.; Follstad Shah, J.; et al. Standards for ecologically successful river restoration. *J. Appl. Ecol.* **2005**, *42*, 208–217. [[CrossRef](#)]
46. Bruder, A.; Tonolla, D.; Schweizer, S.P.; Vollenweider, S.; Langhans, S.D.; Wüest, A. A conceptual framework for hydropeaking mitigation. *Sci. Total Environ.* **2016**, *568*, 1204–1212. [[CrossRef](#)]
47. Ward, J.V. The four-dimensional nature of lotic ecosystems. *J. N. Am. Benthol. Soc.* **1989**, *8*, 2–8. [[CrossRef](#)]

48. Zolezzi, G.; Siviglia, A.; Toffolon, M.; Maiolini, B. Thermopeaking in Alpine streams: Event characterization and time scales. *Ecohydrology* **2011**, *4*, 564–576. [[CrossRef](#)]
49. Petts, J.; Leach, B. *Evaluating Methods for Public Participation: Literature Review*; Environment Agency: Bristol, UK, 2000.
50. Jansson, R.; Nilsson, C.; Dynesius, M.; Andersson, E. Effects of river regulation on river-margin vegetation: A comparison of eight boreal rivers. *Ecol. Appl.* **2000**, *10*, 203–224. [[CrossRef](#)]

Publisher’s Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



© 2020 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0/>).