Interactive comment on "Global scale human pressure evolution imprints on sustainability of river systems" by S. Ceola et al.
Response to Wouter Berghuijs (Referee)

The authors gratefully acknowledge Wouter Berghuijs for his positive and extremely detailed review. In what follows in *italics* are the comments provided by the Referee, and in **bold** fonts the authors' response, inclusive of the indication on how the text will be modified within the next days to comply with the Referee' recommendations and comments.

This paper presents an interesting and novel analysis of how human pressures on river systems have evolved over the period 1992-2013 for over 2000 rivers globally. The paper introduces the metric "Differential Human Pressure on Rivers" to quantify human pressures on rivers. The paper defines Human pressure on rivers as the ratio between the cumulative human presence and activity across the contributing area (here: sum of nightlights) and the natural discharge generated within the same contributing area. Applying this metric to river flow and nightlight data indicates that, on average, human pressure has slightly increased on river systems (+1.6% per year over the 1992-2013 period). These results also indicate hotspots of change (e.g. northern tropical and equatorial areas). The paper states this offers guidance on where the development and implementation of mitigation strategies and plans are most needed.
This paper addresses a relevant topic and therefore is potentially very suitable for publication in HESS. The results that are presented are interesting. Overall the paper is relatively clearly written and I enjoyed reading it.

The authors wish to thank Wouter Berghuijs for his recognition of our research idea and his overall appreciation of the manuscript.

However, before I can recommend publication of this work, several things need to be clarified.

Please see our detailed replies below. The revised manuscript including the suggested changes, if accepted, will be uploaded in the next few days.

Why normalize by river discharge? It seems that changes in pressure on river systems (DHPR) are mathematically independent of a location's discharge (since DHPR looks at relative changes and runoff is assumed constant per location). Thus, the "Differential Human Pressure on Rivers" solely quantifies changes in nightlight data along a river network. This is not wrong, but this does not match the description that is used throughout the paper.

We normalized by river discharge to distribute human presence and activity on natural available discharge, following the approach developed by Vörösmarty et al. (2010). DHPR is based on the analysis of the temporal evolution of standardized human pressure on rivers $F_i(t)$, as defined by Eq. (10) in the original manuscript. Standardized human pressures, and thus DHPR, are a function of the (i) ratio between human presence and activity, HP_i, and discharge, Q_i, and (ii) its minimum and maximum values, which consider both HP and Q. As a consequence, DHPR is not totally independent of Q. Our approach, as defined in this manuscript, considers stationary discharge. However, it is planned in the near future to consider time varying natural flows, to explicitly embed variations in both drivers. As an example, we performed a preliminary study on a few catchments across China and Myanmar, using discharge data provided by GRDC (Global Runoff Data Centre). Standardized human pressures on rivers are reported in Fig. R1, where a comparison between time varying and constant discharge is shown.
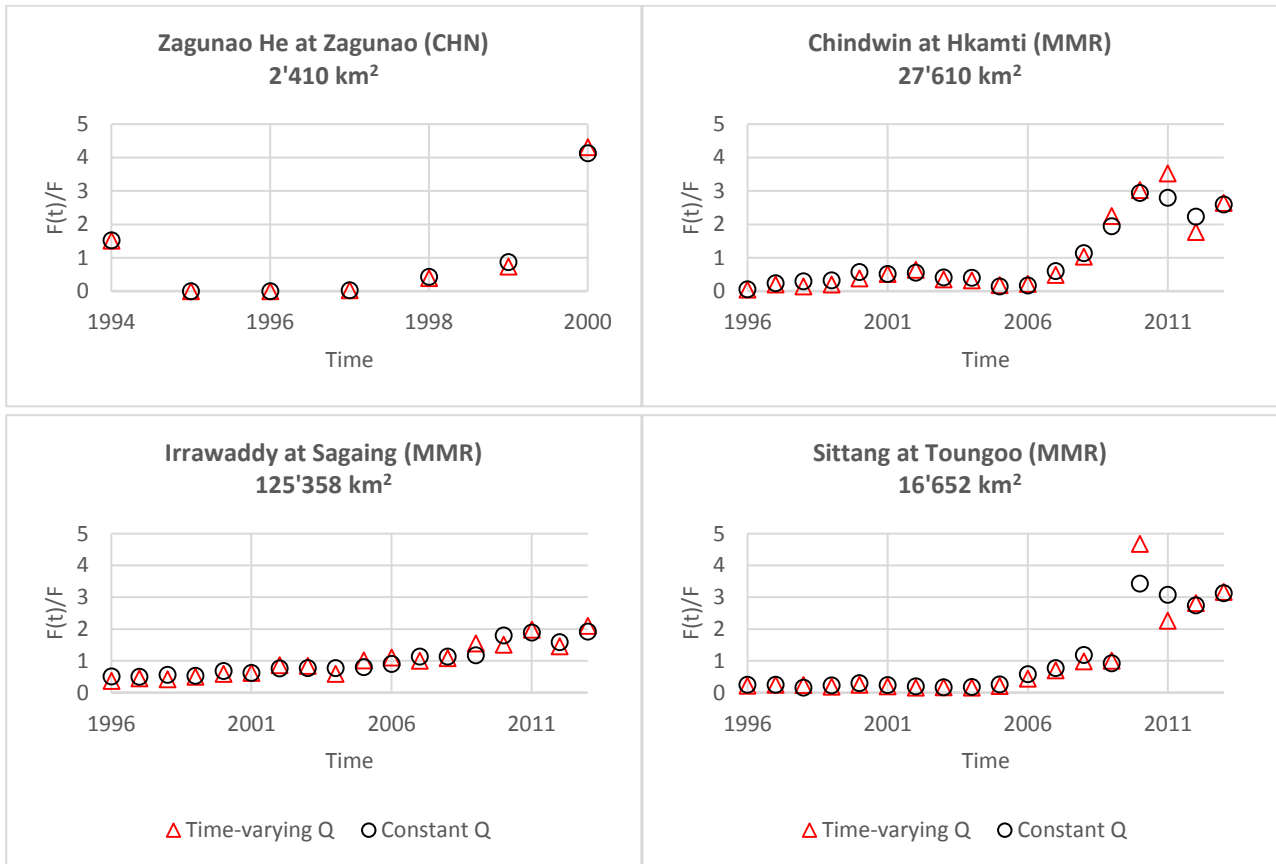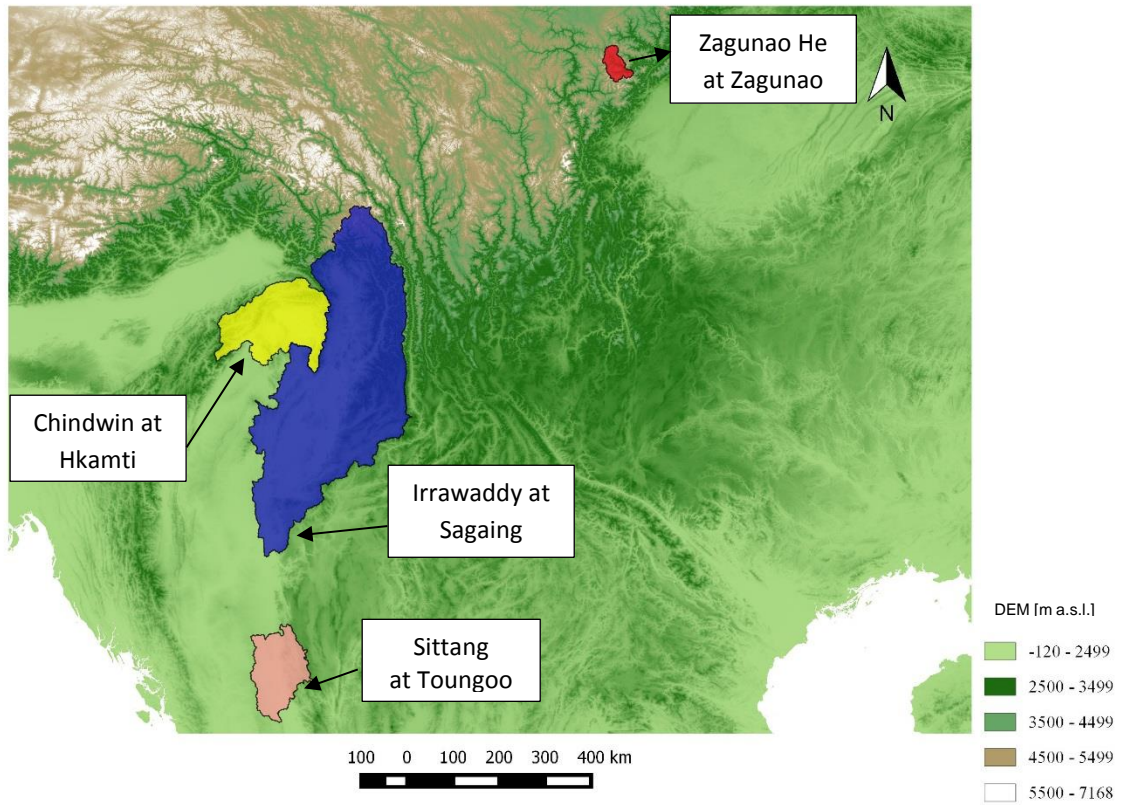
Figure R1. Standardized human pressure on rivers: preliminary results using time varying discharge data to compute the evolution of human pressure on river systems across four catchments in China and Myanmar. A comparison with constant discharge values is also shown.

To what extent is nightlight data representative for human pressure on rivers? I understand that nightlight data is actually a useful proxy for "human presence and activity" but whether it is a good proxy for human pressure ON RIVER SYSTEMS is never shown. Sure, we expect that places with no nightlight tend to have very little human pressures on the river system, and that places with a lot of nightlight data, potentially have a great influence on river systems. However, many aspects that most greatly pressure river systems (e.g. irrigation, dams, etc.) are probably not necessarily very correlated with nighttime data?. I do not say this because I think nighttime data is not useful, I just think it would be very helpful to make clearer/discuss to what extent nighttime data represents actual pressures ON THE RIVER SYSTEMS.

In our manuscript we state that the ratio between nightlight and river discharge can be considered a useful proxy for human pressure on river systems. The reason to assume this stems from the statistically significant correlation with existing and well acknowledged datasets, such as water threats (Vörösmarty et al., 2010) and human footprint (Sanderson et al., 2002; Venter et al., 2016), which propose complex and data-demanding metrics to measure human pressure on natural systems. Our approach, although relatively simple, defines human pressure on rivers as a basin scale cumulative effect of residing population and its economic activities on the natural river discharge at the basin outlet. In other words, we focus on (1) how many people live and act on a river basin (namely, the sum of nightlights) and (2) in which way this anthropogenic effect is diluted with river discharge. Local aspects such as dams and water withdrawals for civil, industrial and irrigation purposes are not taken into account. Therefore, nightlights and river discharge are considered the sole controlling and the best representative drivers of human pressure on rivers. Our analysis allows to quickly assess human pressure on rivers, with several potentialities for the identification of hot spot areas of change in pressure. This part will be added in the revised manuscript.

To what extent are changes in time in nightlight data representative for changes in time? The validation of DHPR is done on a spatial comparison with previously used metrics. What makes you confident that the metric can meaningfully quantify changes in time in human pressure (rather than characterize differences in space)?

Thanks for this remark. This is a quite challenging task (also linked to your previous question), since to our knowledge there is no availability of alternative metrics that show changes in time of human pressure on rivers. One could use, as also reported in the manuscript, population gridded data (e.g. Gridded Population of the World, or Global Human Settlement Layer), as an alternative proxy of human presence and activity. However, these datasets present several limitations (exponential growth model, uniform densities across a municipality), which do not allow for a robust validation in time. If you are aware of any additional dataset which shows changes in time of human pressure on rivers, we will be happy to elaborate more on this.

What makes a hotspot a hotspot Hotspots can be identified based on absolute pressure, or changes in pressure. The focus in this paper seems on the latter. However, these are all "relative changes" in pressure, but is a relative change really relevant when the "absolute pressure" is very low"?

Thanks for this comment. To better explain this issue and reply to your question, we show in Fig. R2 a comparison among (a) the relative change in pressure, DHPR, (b) the long term average standardized human pressure on river systems $\overline{F}$, where the value at the outlet is uniformly distributed across each river basin, and (c) the absolute change in pressure, as the product between DHPR and $\overline{F}$. Marked absolute changes in pressure are evident only for river basins with relatively high standardized human pressures. These absolute changes, expressed

as % per year, are evidently proportional to absolute pressures and thus it is not possible to compare trends across basins. We used normalized values of human pressure in order to compare trends at global scale, independently from absolute human pressure values, which are influenced by catchment size, human presence and activity (namely, the sum of nightlights) and discharge.

To what extent do the results say anything about human security and sustainable development Result are often put in these big terms. For example "Our study identifies critical zones where the change rate of human pressure will undermine human security and sustainable development in the near future." This statement seems unfounded and a strong overinterpretation of the results. Undermine human security? Sure, this may be related to your index, but that cannot be seen from any of the results that you have (any linkage there is purely speculative and not scientifically shown by your work). I would suggest to tone down the interpretation a bit, and more focus on the facts that you actually show

Thanks for this remark. This statement, as also reported below as a reply to one of your questions, will be toned down.

Detailed comments below Note that, at times, "buzzwords" with an unclear/unspecific meaning are used which makes it for me difficult to follow at times) I made some suggestions in the detailed comments below, but this is not necessarily exhaustive. I would encourage using clearly defined terms throughout the paper. I think all these issues can be addressed with textual changes, and I look forward to seeing a final version being published soon in HESS.

Thanks again for your positive comments. We will modify the text, accordingly to your suggestions.

Detailed comments

Throughout the entire paper: "Vorosmarty" should be "Vörösmarty".

Ok.

Page 1

L2: The part "with severe implications for anthropogenic activities and river ecosystems" seems redundant and makes the sentence slightly awkward to read.

Ok, this part will be removed.

L3: "was already exposed" instead of "was exposed [. . .] already".

Ok, thanks.

L4: can you be more specific than "these threats (to water security)"? If no, that's ok. If yes, that would be helpful. That water security is becoming an increasingly relevant topic is namely not new. Quantifying its changes is.

We agree that introducing water security in the abstract of the manuscript without a precise contextualization may be distracting. For this reason, in the revised manuscript we will remove the term "water security" and use "human pressure". The sentences will read: "Previous studies showed that a large part of global river systems was already exposed to relevant anthropogenic pressures at the beginning of this century. A relevant question, which was never explored by the literature so far, is whether these pressures are increasing in time, therefore representing a potential future challenge to the sustainability of river systems."
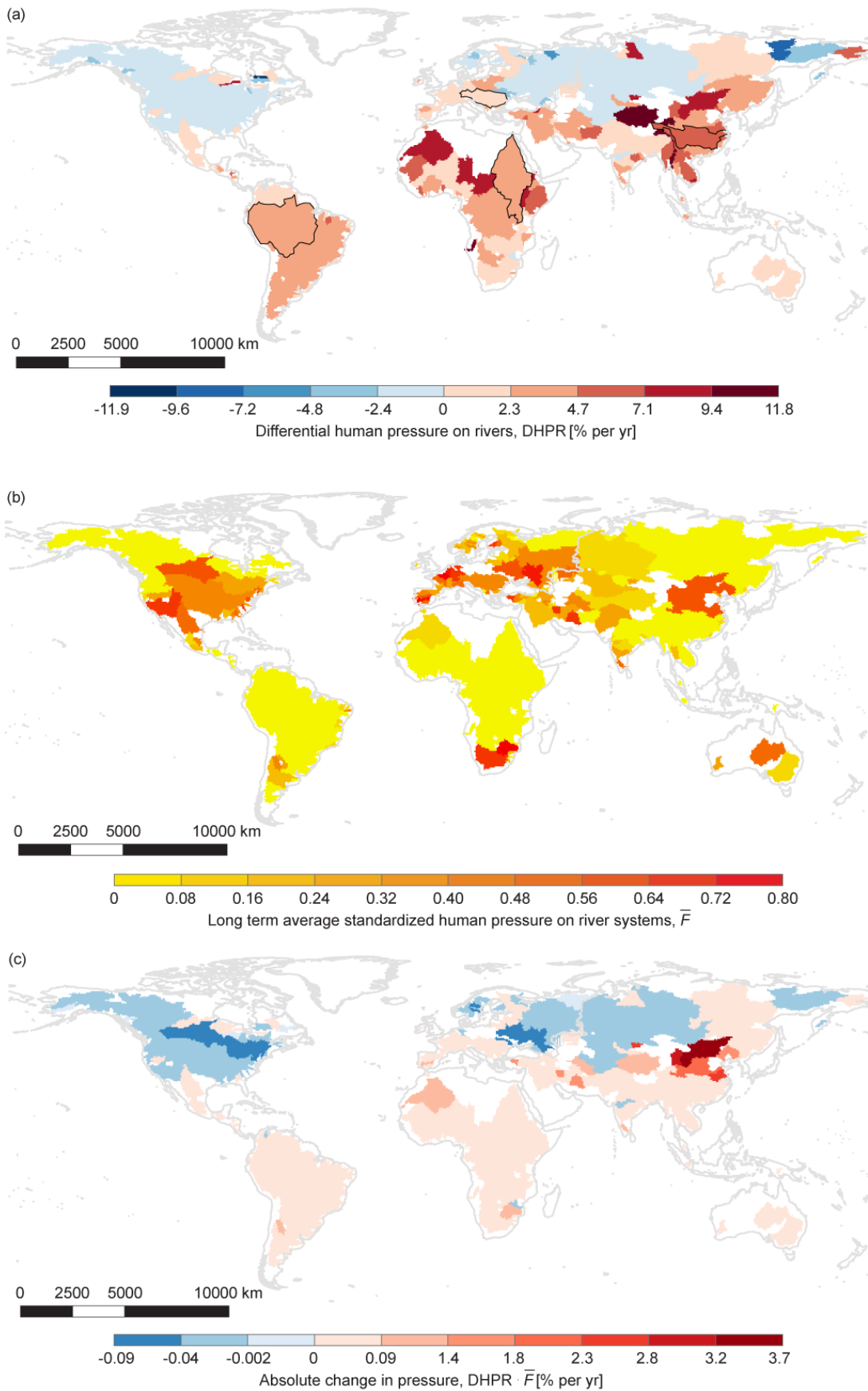
Figure R2. Global distribution of (a) relative change in human pressure on river systems, DHPR (% per year), (b) long term average standardized human pressure on river systems, $\overline{F}$, where the value at the outlet is uniformly distributed across each river basin, and (c) the absolute change in pressure (% per year), as the product between DHPR and $\overline{F}$.

L5: I would suggest to remove "simple, objective and effective". All these qualifications are arbitrary, and I would let the reader decide to what extent this is the case.

Agreed.

L6: "to quantify" instead of "to measure".

Ok.

L7: normalized human pressures "on river systems" (considering adding the last past for clarity).

Ok, thanks.

L8: "time invariant discharge data" sounds odd. The data itself is not time invariant, which this wording suggests (to me). Maybe use "time-averaged" which is nearly the same but seems to be a better fit (to me).

Instead of using "time invariant" we will use "stationary".

L9-11: This sentence reads a bit odd. Consider "The results show that normalized annual human pressure on river systems increased globally, as indicated by an average DHPR value of 1.9% per year, whereby the greatest increases occurred in the northern tropical and equatorial areas."

Perfect, thanks for the suggestion.

L10: It seems to me the units of change (DHPR) are % per year, not %?

Right. We will modify units of measurement for DHPR along the entire manuscript.

L12: "the development and implementation of mitigation strategies and plans" is very unclear to me. I guess that's ok, but if you can be more precise that would be helpful.

We prefer to keep this sentence as is. Our approach can quickly identify hot spot areas of change and thus help towards the definition of possible strategies aimed at controlling the evolution in time.

L15: Consider something like "have been extensively reported" instead of "than have been well established". OK, maybe my suggestion is not great either, but "established" seems to be an odd verb to use here.

Your suggestion sounds reasonable and better that our original version. The text will be modified accordingly.

L16: "Increasing" instead of "Enhancing".

Ok.

L21-22: Consider "how human pressure on river systems can be sustainable in the long term" instead of "if human pressure on river systems is going to be sustainable in the long term."

Fine.

Page 2

L2: Consider "be assessed" instead of "be then inspected"

Ok.

L3-4: "in sensitive areas" seems to be redundant/or unnecessarily specific?

Ok, this part will be removed.

L13: "this analysis" or "such analyses"?

We prefer to keep the sentence as is.

L14: "allow" or "provide"?

We accept your suggestion and in the revised manuscript we will use "provide".

L14-15: "for the analysis and identification of the main drivers of human pressure on river systems" or "to analyze and identify human pressures on river systems"

This sentence in the revised manuscript will read: "Powerful tools are now available to carry out this analysis. Earth system modeling and remote sensing observations have produced global datasets that provide unprecedented possibilities to analyze and identify human pressures on river systems, as well as their progress in time."

L19: Consider being explicit that you propose "A simple and effective methodology" (rather than "is proposed" which makes it unclear who has done this).

Thanks for this. In the revised manuscript the sentence will read "We propose…".

L23-24: "which epitomize surface hydrological processes within a river basin and represent the river natural flow regime" seems redundant (first part) and not necessarily accurate (second part), so I would suggest to remove it.

We partly accept your suggestion and here it is our revised sentence "Natural discharge values, which epitomize surface hydrological processes within a river basin, are computed from runoff data.".

Page 3

L6: "concluding" instead of "conclusive".

Ok.

L9-11: "The Simulated Topological Network STN-30 (Vorosmarty et al., 2000a, b; Fekete et al., 2001) was the digital river network used in this work."

This comment is not clear. Could you please provide us a feedback?

Page 4

L3: "which overcomes" instead of "which overcome"

Ok.

L25-28: "The computational steps explicitly incorporate catchment topology and use a routing scheme based on flow directions to evaluate the downstream accumulation of human presence and activity and natural river discharge" It seems that in the end the method does not incorporate river discharge?

The method evaluates the downstream accumulation of human presence and activity and river runoff, defined as the sum of nightlights and natural river discharge, respectively. In the revised manuscript, we will use "runoff" instead of "discharge".

Page 5

L13: Can you explain why "Standardization was essential to test the reliability of the proposed methodology."?

This sentence is connected to the following one. An "indeed" will be added to better clarify this point.

L22: "clearly" seems redundant (and arbitrary).

Ok.

L24: the unit is % per year? not %?

Yes, thanks.

Page 6

Line 24: "Student's T-test" or "Student's t-test"?

We will use "Student's *t*-test" throughout the whole manuscript.

Section 2.4: Can you comment on why a significant correlation in SPACE between this variable and previous metrics warrants the use of DPHR (which quantifies changes in TIME)?

As also stated above, to support the reliability of our metric of human pressure on rivers, we compared it against existing methodologies. The goal was to prove that our method provides results similar to previous metrics, but, differently from them, it allows the analysis over time. Thus, given the statistically significant correlation among the considered variables, our metric of human pressure on rivers can be used as a reliable variable and then changes in time can be quantified. We will change the text as follows: "We computed P-values from the Student's *t*-test and the coefficient of determination R² to check the statistical significance of the regression analysis. A statistically significant correlation in space between our estimates of human pressure on rivers and previous metrics warrants the use of the proposed variable as a valuable alternative. In addition, given the availability of time series, it allows the quantification of changes in time.".

Page 7

L5: what do you mean by "and then consolidated by region", do you mean "grouped by region"?

Yes, the manuscript will be changed accordingly.

L9: "extent", not "extension"?

Ok.

L33: I do not know why does would "clearly imply severe endangerment levels" (beyond a reader's own interpretation)? what does "severe endangerment levels" actually mean here?

High human pressure values well correlate with high water threats and human footprints, which identify high risk conditions (i.e. severe endangerment levels). If needed, we can change this sentence in the manuscript.

Page 8

L2: "human footprint focuses on the entire terrestrial realm and does not explicitly consider river systems" can you be more precise/specific here? I do not know what this means.

Thanks for this remark. We realized that this sentence was not totally accurate and we propose to modify it as follows: "A better correlation was found with water threats, rather than human footprint values. This was expected, since human footprint considers the entire terrestrial realm and does not exclusively focus on river systems.".

L6: what do you mean by "recent outcomes on the terrestrial realm"?

"Terrestrial realm" will change in "terrestrial environment".

L7: Be explicit that you now talk about hot spot regions OF CHANGE.

Ok, thanks.

L8-9: "at an accelerated pace" seems redundant (and is something that is not looked at in this paper), therefore I suggest to delete it.

Agreed.

L11: units are % per year?

Yes, thank you.

L32-33: "DHPR identifies critical zones where increasing trends in human pressure on river systems will undermine human security and sustainable development in the near future." This seems like a strong overstatement to me (i.e. how do we know these areas will "undermine human security and sustainable development in the near future"?). I would really recommend toning down this statement.

Ok, thanks. We will modify the sentence as follows: "DHPR identifies critical zones where increasing trends in human pressure on river systems may undermine human security and sustainable development in the near future.".

L33-34: "River basins located within the northern subtropical and equatorial belts across Africa and Asia clearly epitomize this situation, showing markedly positive change rates in the 1992 to 2013 period". Making a statement on strong positive DHPRs in these regions is fine. I believe you cannot say (from your results) that these numbers simply show "critical zones where increasing trends in human pressure on river systems will undermine human security and sustainable development in the near future".

According to your comment, we toned down and slightly rearranged our sentence, which now reads: "Hot spot areas of change are represented by river basins located within the northern sub

tropical and equatorial belts across Africa and Asia, showing markedly positive change rates in the 1992 to 2013 period.".

Page 9

L8-9: what do you mean by "global sustainability levels of river systems"?

This concept should be linked to human pressure, but we realized that it may be misleading. In our revised manuscript we will remove it and keep only "human pressure on river systems".

L11: "in the near future" seems redundant and overly restrictive.

This will be deleted in the revised version of the manuscript.

L12: "objective and powerful" seem both to be subjective and redundant. Personally, I would let the reader conclude this, rather than make this conclusion for them.

Ok, thanks.

L11-13: "The Differential Human [. . .] needs to be taken" is not a logical sentence. Please rephrase.

This sentence will read: "The Differential Human Pressure on Rivers index (DHPR) proposed here is a simple tool that analyzes for the first time the temporal evolution of human pressure on river systems. DHPR identifies hot spot areas of change, offering guidance on where implementing mitigation strategies."

L13: "identifies areas where priority action needs to be taken" should be removed.

Please refer to our previous reply.

L17: Nightlights and river discharges are [considered] the sole controlling drivers of human pressure on river systems. (add the word considered).

Ok, thanks.

L18: "have been proven", not "have been proved".

Ok.

L17-26: I appreciate that these limitations are discussed. However, I think it is much more relevant to point out the limitation that nightlight data can have very little to do with human pressure on rivers, and is a largely unvalidated proxy for this.

Thanks for this comment. Our original goal here was to simply highlight the technical limits of the data employed in our study. In the revised version we will comment also on this issue. For more details, please refer to our reply above.

L24: these action wont "cast some doubts on nightlight values", they will "cast some doubts on to what extent nightlight values represent the changes you are interested in here".

Thanks for this. The sentence will read: "In addition, light pollution abatement strategies employed to reduce the artificial sky brightness and preserve world's ecosystems, can cast some doubts on nightlight values and on their evolution in time."

L32: The following statement seems at odd with a study that focusses on human pressure on rivers "Furthermore, given that our focus is on natural river systems, [. . .]"

We respectfully disagree. As an initial research, we preferred not to introduce any additional drivers that could influence (and eventually confound) our estimates of human pressure on rivers. Future research will definitely focus on this.

Page 10

L10: I am unsure what "an order zero information" means

Thanks for this remark. In the revised manuscript we will change "an order zero information" in "simplified information".

L12-13: "Our study identifies critical zones where the change rate of human pressure will undermine human security and sustainable development in the near future." This statement is unfounded and seems like an overinterpretation of the results. Undermine human security? Sure, your results can be related to limited water resources, but your statement is not shown by any of the results that you have.

Thanks for your comment. The sentence will be toned down.

Page 13

Vorosmarty" should be "Vörösmarty

Ok.

Page 15

In the figure, F overline should be in italics?

Yes.

Page 16

Figure 3: In the titles of the subpanels: DHPR should be in units % per yr?

Yes, thank you.

Interactive comment on " Global scale human pressure evolution imprints on sustainability of river systems " by S. Ceola et al.

Response to Anonymous Referee #2

The authors gratefully acknowledge the Referee for his/her fully supportive review. In what follows in *italics* are the comments provided by the Referee, and in **bold** fonts the authors' response, inclusive of the indication on how the text will be modified within the next days to comply with the Referee' recommendations and comments.

This is a thoughtful and well written paper that demonstrates the effects of human activities on rivers around the world. The nightlight satellite data allow a more consistent and meaningful analysis of the changes of these effects than alternative data sources. The description is clear, the analysis complete, and the interpretation convincing.

We wish to thank the Referee for his/her important appreciation.

I only have one concern with the paper. The authors introduce a "Human pressure index" based on nightlight data but are not clear what processes exactly this index is to capture and why. Is the index a surrogate of consumptive use of irrigation water? In this case, one would have to argue that irrigation differs immensely around the world for the same light intensity. Also, what is the process reasoning that consumption is proportional to the use of light? I do not disagree with the concept, but it would be good to extend the justification. In some regions the index may be a surrogate of contamination of rivers, or changes to river morphology perhaps? Again, a full discussion of the processes the index is supposed to represent would be useful. This justification would also help in the discussion section of the paper which is currently mainly focusing on the limitations of the method, while the implications for water management should be added.

Thanks for this comment, which allows us to better explain our reasoning. Our approach, although relatively simple, defines human pressure on rivers as a basin scale cumulative effect of residing population and its economic activities on the natural river discharge at the basin outlet. In other words, we focus on (1) how many people live and act on a river basin (namely, the sum of nightlights) and (2) in which way this anthropogenic effect is diluted with river discharge. Local aspects such as dams and water withdrawals for civil, industrial and irrigation purposes are not taken into account. Therefore, nightlights and river discharge are considered the sole controlling and the best representative drivers of human pressure on rivers. Our analysis allows to quickly assess human pressure on rivers, with several potentialities for the identification of hot spot areas of change in pressure. This part will be added in the revised manuscript - section "Discussion and Conclusion".

Recommendation: I recommend publication of the paper with minor changes. I suggest the authors elaborate on the process basis of the index to further strengthen the paper.

Thank you again.

Global scale human pressure evolution imprints on sustainability of river systems

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Abstract. Human pressures on river systems pose a major threat to the sustainable development of human societies in the twenty first century~~, with severe implications for anthropogenic activities and river ecosystems.~~. Previous studies showed that a large part of ~~the global population was~~ global river systems was already exposed to relevant ~~threats to water security already~~ anthropogenic pressures at the beginning of this century. A relevant question, which was never explored by the literature so far, is whether these ~~threats~~ pressures are increasing in time, therefore representing a potential future challenge to the sustainability of river systems. This paper proposes ~~a simple, objective and effective~~ an index we call Differential Human Pressure on Rivers (DHPR) to ~~measure~~ quantify the annual evolution of human pressure on river systems. DHPR identifies a per year percentage increment (or decrement) of normalized human pressures on river systems (i.e., ratio of annual values to long term average). This index, based on annual nightlights and ~~time invariant~~ stationary discharge data, is estimated for 2195 major river basins over a period of 22 years, from 1992 to 2013. The results show that normalized annual human pressure on river systems increased globally~~by a DHPR value equal on average to~~, as indicated by an average DHPR value of 1.9% ~~and that~~ per year, whereby the greatest increase occurred ~~within~~ in the northern tropical and equatorial areas. The evaluation of DHPR over this 22 year period allows the identification of hot spot areas, therefore offering guidance on where the development and implementation of mitigation strategies and plans are most needed (i.e., where human pressure is strongly increasing).

1 Introduction

The detrimental effects of anthropogenic activities on river systems have been ~~well established (Barnett et al., 2008; Haddeland et al., 2014; Enhancing~~ extensively reported (Barnett et al., 2008; Haddeland et al., 2014; Padowski et al., 2015; Steffen et al., 2015; UNWWAP, 2015; Increasing anthropogenic activities, demographic expansion and the improvement of living standards are threatening sustainability at a global level. The development of human activities and associated human pressure on river systems often results in the emergence of threats to water security, from both human and river biodiversity perspectives (Vörösmarty et al., 2000c, 2010; Falkenmark, 2013; Wada and Bierkens, 2014; World Economic Forum, 2015; Kummu et al., 2016; Mekonnen and Hoekstra, 2016). There is a urgent need to manage and guide this development by strategies that consider ~~if~~ how human pressure on river systems ~~is going to~~ can be sustainable in the long term.

Human water interactions controlling human pressure on river systems should be analyzed at a detailed level, based on a local knowledge of the spatial distribution of river discharge, human population and associated interrelationships (Kummu et al., 2011; Meybeck et al., 2013). In order to compare, identify and prioritize areas of high human pressure across the globe, estimates of human pressures should be ~~then inspected~~ assessed at global scale. Understanding the spatial and temporal patterns in human pressure on river systems is fundamental for the development and implementation of targeted strategies ~~in sensitive areas~~.

A first high resolution global scale assessment of human pressure on river systems (Vörösmarty et al., 2010) showed severe water threat levels for nearly 4.8 billion people. In that study, the most threatened areas were located across the United States, Europe, central Asia, India, eastern China and the Middle East. While that analysis showed the relevance and extent of the problem and the need to take action, it is now important to understand how this issue developed and how it is likely to progress in time. Only when the historic development and the key factors that triggered it are understood, reality based targets can be established and sound strategies can be developed. In this context, recent efforts focusing on the terrestrial system provided updated estimates of the global human footprint (Sanderson et al., 2002) monitoring changes from 1993 to 2009 (Venter et al., 2016a, b).

Powerful tools are now available to carry out this analysis. Earth system modeling and remote sensing observations have produced global datasets that ~~allow unprecedented possibilities for the analysis and identification of the main drivers of human pressure~~ provide unprecedented possibilities to analyze and identify human pressures on river systems, as well as their progress in time. There is information on human presence and activity (EC-JRC, 2015; CIESIN, 2016; NOAA, 2017), river and watershed delineation (Lehner et al., 2008; Fekete et al., 2001), river discharge (Fekete et al., 2002), water related threats (Vörösmarty et al., 2010) that can be analyzed independently or combined to provide insights of human water interactions.

~~A simple and effective methodology is proposed~~ We propose a methodology for analyzing and mapping the historic evolution of human pressure on rivers. Given a river site and its contributing area, human pressure on river systems is defined as the ratio between the cumulative human presence and activity across the contributing area and the natural discharge generated within the same contributing area. We estimate human presence and activity, which is mainly linked to population density and level of development, by analyzing nightlights, retrieved from satellite images monitoring nocturnal luminosities. ~~Discharge~~ Natural discharge values, which epitomize surface hydrological processes within a river basin ~~and represent the river natural flow regime~~, are computed from runoff data. Nightlights and river runoff are selected as the key variables to calculate human pressure on river systems because of the availability of valuable global scale and spatially explicit data that allows the analysis over time. More specifically, we compute human pressure on river systems on an annual basis, where human presence and activity varies across years, while natural discharge is assumed to be ~~time invariant~~ stationary during the study period. We therefore take the catchment as the spatial entity whereon human pressure on river systems is evaluated, and then measure its annual evolution by defining the Differential Human Pressure on Rivers index (DHPR). DHPR is computed as the annual time derivative of human pressure on river systems and identifies a per year percentage increment (or decrement) of normalized human pressures (i.e., ratio of annual values to long term average). Global scale DHPR values are estimated for the period 1992-2013 for 2195 major river basins. DHPR can be used to identify hot spot areas of change where there is a marked and consistent

increase of human pressure on river systems over time. This is valuable information on which a robust planning strategy can be based, targeting actions to address water threats in key areas and bearing important implications for a sustainable development of human societies close to river systems in the near future. To prove the validity of our methodology, the relationship between human pressure on river systems and existing datasets, i.e., water threats (Vörösmarty et al., 2010) and the terrestrial human footprint (Venter et al., 2016a), is investigated. Global values of human pressure are contrasted with the corresponding water threat and human footprint values.

The manuscript is organized as follows. In Sect. 2 we describe the data and the methodology developed for the estimation of global scale DHPR values, including also the correlation analysis with alternative datasets. The main outcomes are reported in Sect. 3. Results are then discussed in Sect. 4, including also some ~~conclusive~~ concluding remarks.

2 Materials and Methods

2.1 Global scale river network and runoff data

The Simulated Topological Network STN-30 (Vörösmarty et al., 2000a, b; Fekete et al., 2001) was the digital river network used in this work. The STN-30 river network originates from a 0.5° flow direction grid (i.e., nearly 55 km at the equator) and offers many different river attributes, such as drainage area, river length, distance to river outlet and river basin delineation. We compute average annual natural river discharge as derived from the Global Composite Runoff Fields dataset (Fekete et al., 2002), which provides long term mean annual runoff data along the STN-30 river network. Natural river discharge was derived from a routing scheme based on flow direction paths along the STN-30 as follows (see Fig. 1B and Fig. S1C):

$$Q_i = \sum_{j=1}^{N_i} R_j \cdot A_j, \tag{1}$$

where Q_i [km^3 yr^{-1}] is the long term mean annual discharge in any grid cell i, R_j [km yr^{-1}] and A_j [km^2] are the long term mean annual specific runoff (i.e. per unit area) (Fekete et al., 2002) and the area of grid cells j, respectively. The identifier N_i is coincident with the number of upstream grid cells j.

2.2 Global scale data on human presence and activity

There are several possibilities for the estimation of human presence and activity at high spatial resolution globally. Traditional datasets that provide gridded data on population densities and/or gross domestic product (GDP) estimates could be employed. The Gridded Population of the World, developed by the Center for International Earth Science Information Network at Columbia University, and the Global Human Settlement Layer, provided by the European Commission, Joint Research Centre, are the most acknowledged datasets on population densities. The Gridded Population of the World dataset provides population counts and densities for the years 2000, 2005, 2010, 2015, and 2020 (extrapolated from 2010 population data) at 0.0083° resolution (i.e., nearly 1 km at the equator) for the entire globe. However, constant population densities are provided within each census unit, thus resulting in a significant limitation for the proposed analysis. Differently, the Global Human

Settlement Layer dataset, provides a spatial variability within censuses at either 1 km or 250 m spatial resolution. However, this dataset offers a temporal evolution of population densities for the years 1975, 1990, 2000, and 2015 estimated from an exponential growth model that uses limited ground based data. Concerning GDP estimates, a temporal sequence of gridded datasets at the global scale is not available to date. Yearly country based GDP values are usually provided, even though some developing countries may present low quality statistical data.

An alternative dataset is represented by nightlights, which ~~overcome~~ overcomes some major limitations of the aforementioned ones. Nightlights are used in this work as a proxy for human presence and activity, being the best available option to analyze and map the evolution of global scale human pressure on river systems both in space and time. Nightlights are satellite data derived from the United States Air Force Defense Meteorological Satellite Program (DMSP). The satellites are equipped with Operational Linescan System (OLS) sensors and the information collected is freely provided by the National Oceanic and Atmospheric Administration's National Geophysical Data Center (NOAA, 2017). Stable light composites, available as raster products, are employed here. They monitor the global distribution of nocturnal luminosities associated with anthropogenic activities. More specifically, nightlights provide combined information on human presence and economic activities, as high luminosity can refer to either highly populated or major capital investment areas. Nightlights have been extensively employed as a proxy for human presence and activity for several purposes such as population (Elvidge et al., 1997; Small, 2004), urban (Cauwels et al., 2014) and poverty mapping (Elvidge et al., 2009a; Jean et al., 2016), flood risk, (Ceola et al., 2014; Mard et al., 2018) economic analysis (Chen and Nordhaus, 2011), and light pollution (Bennie et al., 2014).

Nightlight values are expressed as Digital Numbers (DN) that range from 0 (pitch dark areas) to 63 (brightest areas) and they are produced on a yearly basis from 1992 to 2013 (i.e., each pixel shows an average luminosity within a year). Nightlights are provided at 0.00833° spatial resolution and cover areas within 75°N and 65°S, 180°W and E. Six different satellites collected nightlight data during the observation period, with overlapping satellites during some years (from 1997 to 2007). In the case of multiple satellites operating simultaneously, an average value between the two simultaneous satellites was computed in order to obtain unique yearly nightlight values. Since nightlight products are not on board calibrated, a well established intercalibration procedure was performed (Ceola et al., 2014, 2015; Chen and Nordhaus, 2011; Elvidge et al., 2009b), before computing human pressure on river systems.

2.3 Historic evolution of global scale human pressure on river systems: computational steps

The Differential Human Pressure on Rivers index (DHPR) was derived from the analysis of the historic evolution of annual values of human pressure on river systems. The computational steps explicitly incorporate catchment topology and use a routing scheme based on flow directions to evaluate the downstream accumulation of human presence and activity and natural river ~~discharge~~ runoff.

Given a river site and its contributing upstream area, annual values of human pressure on river systems $f_i(t)$ [km^{-3} yr] were defined as the ratio between the cumulative human presence and activity across the contributing area $HP_i(t)$ [-] and the long

term average natural river discharge generated within the same area Q_i [km^3 yr^{-1}], see Eq. (1). Namely,

$$f_i(t) = \frac{HP_i(t)}{Q_i}.$$ (2)

where i identifies a generic river network grid cell and t represents the study year, from 1992 to 2013. The term "cell" below always refers to 0.5° by 0.5° grid cell, as defined by the STN-30 river network here employed (Vörösmarty et al., 2000a, b;

5   Fekete et al., 2001). Overall, data from 20770 grid cells for 2195 river basins were used. The cumulative human presence and activity $HP_i(t)$ [-] in any grid cell i was calculated from contributing upstream cells as routed nightlight values by using (see Fig. 1A and Fig. S1A,B):

$$HP_i(t) = \sum_{j=1}^{N_i} NL_j(t),$$ (3)

where $NL_j(t)$ represents summed nightlight values in grid cells j for year t (i.e., the value of pixels for nightlights at 0.00833°

10   resolution were summed to 0.5° by 0.5° grid cells) and N_i is the number of upstream cells j. Grid cells with null nightlight data throughout the whole study period were discarded.

In order to estimate the historic evolution of human pressure on river systems across the entire globe, annual values of $f_i(t)$ were first standardized to a dimensionless 0-1 scale $F_i(t)$ as follows (see Fig. 1C):

$$F_i(t) = \frac{f_i(t) - min(f_k)}{max(f_k) - min(f_k)}$$ (4)

15   where k identifies a generic grid cell where f_k is either the absolute minimum or maximum value of $f_i(t)$ across all considered grid cells and years. The long term average of standardized human pressure on river systems $\overline{F_i}$ was then computed as the mean of annual values from 1992 to 2013. Standardization was essential to test the reliability of the proposed methodology. ~~Standardized~~ Indeed, standardized human pressure values were contrasted with existing well acknowledged datasets, i.e., water threats (Vörösmarty et al., 2010) and the terrestrial human footprint (Venter et al., 2016a), by performing a regression analysis

20   (see Section 2.4). The historic evolution of standardized human pressure values was assessed by performing the following linear regression:

$$\frac{F_i(t)}{\overline{F_i}} = a_0 + DHPR_i \cdot t + \epsilon(t),$$ (5)

where $DHPR_i$ [yr^{-1}] is the Differential Human Pressure on Rivers index in grid cell i, a_0 is the intercept, and $\epsilon(t)$ represents regression residuals. DHPR represents the relative change rate (i.e., a percentage increment or decrement) of normalized

25   human pressure values, defined as the ratio between annual and long term average standardized values of human pressure. We employed normalized human pressure values to easily compare relative change rates at the global scale. Positive (or negative) DHPR values ~~clearly~~ correspond to increasing (or decreasing) trends of human pressure on river systems in the study period. Null DHPR values identify a time invariant behavior (i.e., significant changes in time are not detected). For example, a value of DHPR equal to 4% per year represents the condition for which normalized human pressure on river systems increases

30   on average every year of 4% with respect to its initial condition (i.e., in 1992). Thus in the 22-year study period, there is

a 88% relative increment of $F_i(t)/\overline{F_i}$ values. Without any normalization, change rates of human pressure would have been proportional to standardized values $F_i(t)$, which clearly depend on the contributing area, nightlight values and river discharge data. By computing a relative increment (or decrement) of human pressure on river systems, the DHPR index is expected to be a valuable tool, particularly for scarcely illuminated regions. P-values from the Student's ~~T-test~~ *t*-test and coefficients of
5   determination R^2 were computed for each river basin to test the statistical significance of the linear regression given by Eq. (5).

2.4   Correlation analysis between estimates of human pressure on river systems and existing global scale datasets

In order to test the reliability of the proposed approach, we compared our estimates of human pressure on river systems with well acknowledged datasets based on different methodologies. Two alternative datasets were used for this comparison: (i) water threats to human water security and river biodiversity (Vörösmarty et al., 2010) and (ii) human footprint (Sanderson
10   et al., 2002; Venter et al., 2016a, b).

Water threat values, defined by Vörösmarty et al. (2010), identify either human water security or river biodiversity threats and represent the level of endangerment of river systems. Estimates of water threats derive from a routing scheme based on a combination of 23 drivers normalized by the natural river discharge. Global scale water threat data are provided as a map on the status of river systems at a given location and at a particular point in time, around the year 2000, with a 0.5° resolution. For
15   our correlation analysis we used gridded water threat data, freely available at http://www.riverthreat.net/index.html. Although human water security and river biodiversity threats are strongly correlated, in this paper we opted to examine both threats.

Human footprint estimates, developed by Sanderson et al. (2002), provide a measure of human pressure on the environment. Human footprint considers the entire terrestrial realm and not only river systems. Human footprint values on land areas are derived from 8 different proxy variables for human pressure. Normalized cumulative values identify the percentage of relative
20   human influence within a region. Global scale gridded data of human footprint are available for years 1993 and 2009 at 0.00833° resolution (doi:10.5061/dryad.052q5, see also Venter et al., 2016b). For our correlation analysis, we used data from both years and averaged the value of pixels for human footprint at 0.00833° to 0.5° by 0.5° grid cells.

Standardized values of human pressure on river systems $F_i(t)$ computed in any grid cell i were contrasted with water threat and human footprint data. This relationship was investigated by performing the following log-lin regression analysis:

25    $$log_{10}F_i(t) = m_X \cdot X_i(t) + b_X + \epsilon_X \tag{6}$$

where $X_i(t)$ identifies either water threat or human footprint values in grid cell i, m_X represents the slope of the log-lin regression line, b_X is the intercept and ϵ_X represents regression residuals. Water threat values were contrasted with standardized human pressure estimates for year 2000, while human footprint data were compared against 1993 and 2009 estimates. We computed P-values from the Student's ~~T-test~~ *t*-test and the coefficient of determination R^2 to check the statistical significance
30   of the regression analysis~~and support the applicability of our methodology.~~ . A statistically significant correlation in space between our estimates of human pressure on rivers and previous metrics warrants the use of the proposed variable as a valuable alternative. In addition, given the availability of time series, it allows the quantification of changes in time.

2.5 Regionalization of the Differential Human Pressure on Rivers index

The Differential Human Pressure on Rivers index (DHPR) describes the historic evolution of human pressure on river systems driven by the heterogeneity of anthropogenic activities, hydrological and climatic regimes. DHPR values computed for the considered 2195 river basins were analyzed by considering aggregated spatial regions delineated by river basins (Millennium Ecosystem Assessment, 2005) with similar annual average runoff and temperature. The regions considered were hydrobelts and hydroregions (Meybeck et al., 2013), which incorporate key hydraulic and climatic features driving natural river discharges. Hydrobelts (8 in total, i.e., boreal, northern mid latitude, northern dry, northern sub tropical, equatorial, southern sub tropical, southern dry, southern mid latitude) are classified by maximizing the differences among belts and minimizing the variability within belts; hydroregions (26 in total) are hydrobelts decomposed on a continental basis.

3 Results

Annual values of standardized human pressure on river systems $F(t)$ and the long term average $\overline{F}$ were calculated for 20770 grid cells distributed across 2195 river basins over the period 1992-2013 and then ~~consolidated~~ grouped by region. The regions considered (i.e., hydrobelts and hydroregions, Meybeck et al., 2013) are shown in Fig. 2. Globally, long term average standardized human pressures $\overline{F}$ presented a considerable heterogeneous spatial pattern (Fig. 2), which is to be expected due to the intrinsic variations in the considered drivers (Fig. S1). Standardized human pressure values, ranging from 0 to 1, depend on the spatial ~~extension~~ extent of the contributing area, the level of human presence and activity, as derived from nightlights, and natural discharge values. As a result, large human pressures are typical of river basins with low natural discharges and high human presence and activity. Conversely, low human pressures are generally found across river basins with little human presence and activity and high river discharge. Accordingly, high $\overline{F}$ values were found in the northern mid latitudes and sub tropical regions (i.e., eastern United States, Europe, India and eastern China), whereas low scores were typical of boreal (i.e., northern Russia) and equatorial (i.e., central Brazil and central Africa) areas. Estimates of standardized human pressure could be analyzed by ranking river basins as a decreasing function of either discharge or human presence and activity. When examining the first 15 basins, ranked from largest to smallest natural river discharge (see Table A1), we found $\overline{F}$ values lower than the 90th percentile ($\overline{F}_{90}$=0.426). In particular, 11 out of 15 river basins showed $\overline{F} < \overline{F}_{50}$(=0.055), and 13 out of 15 with $\overline{F} < \overline{F}_{75}$(=0.201). This result was expected, since for larger discharges and assuming equal levels of human presence and activity, lower estimates of standardized human pressure can be found. The regional aggregation proved that the boreal, northern mid latitude and equatorial hydrobelts were equally represented, with 4 river basins each in the first 15. High natural discharges are indeed typical of these three hydrobelts. When ranking river basins as a decreasing function of human presence and activity (see Table A2), we found that 11 out of the first 15 basins were located within the northern mid latitude belt, which is known to be the most populated hydrobelt across the globe. Estimates of human presence and activity within a river basin provide an embedded and combined information about the extension of the contributing area, the total population and the economic activity in that area. This estimate is not directly proportional to the river basin area. Indeed, Amazon, the river basin with the largest drainage area in the world, is not among the 15 largest river basins based on human presence and activity. Large estimates of human presence

and activity do not necessarily correspond to high levels of standardized human pressure, but overall 13 out of 15 river basins showed $\overline{F} > \overline{F}_{50}$.

To test the reliability and consistency of the proposed methodology, standardized values of human pressure on river systems $F(t)$ were contrasted with well acknowledged and consolidated datasets mapping human pressure on terrestrial (Sanderson

5 et al., 2002; Venter et al., 2016a) and freshwater (Vörösmarty et al., 2010) systems. Overall, a consistent worldwide behavior emerged, supported by statistically significant relationships among indices (Table S1). High scores for standardized human pressure on river systems well correlate with high values of both water threat and human footprint, clearly implying severe endangerment levels. A better correlation was found with water threats, rather than human footprint values. This was expected, since human footprint ~~focuses on~~ considers the entire terrestrial realm and does not ~~explicitly consider~~ exclusively focus on

10 river systems. Global and regional results presented a fair data scatter, which reduced when focusing at smaller spatial scales. Our approach based on nightlight and river discharge data cannot explain and totally embed the geographical heterogeneity and the variability of human water interactions. However, it represents a first step forward in mapping the historic development of human pressure and, by focusing on river systems, complements recent outcomes on the terrestrial ~~realm~~ environment (i.e., Human Footprint, Venter et al., 2016b, a).

15 In order to identify priorities and hot spot regions ~~and~~ of change, and thus produce consistent and reliable blueprints to manage human pressure on river systems, it is fundamental to analyze its historic evolution and identify areas where human pressure is increasing~~at an accelerated pace~~. The Differential Human Pressure on Rivers index (DHPR) was calculated at the outlet of the considered 2195 river basins over the period 1992-2013. The global analysis of DHPR revealed positive change rates (Fig. 3), with values within -0.4 ~~%~~ ÷ 3.7% per year (lower and upper quartiles, mean = 1.9% per year, see Fig. 4).

20 Results at the basin scale showed an heterogeneous spatial distribution of change rates, confirming and complementing recent country based outcomes (Worldbank, 2017a; Ceola et al., 2014, 2015). Overall, markedly positive DHPR values were found across river basins with low to moderate standardized human pressure on river systems, whereas regions with high standardized human pressure showed either slightly negative or negligible changes in time. Table 1 reports DHPR estimates for 15 major river basins across the globe. Values for all the considered river basins are provided in Table S2.

25 Individual catchment scale results were aggregated at the regional level. Grouping results by hydrobelt and hydroregion (Meybeck et al., 2013) was a meaningful way to perform this spatial aggregation. In fact, hydrobelts and hydroregions incorporate key hydrologic and climatic features driving average discharge regimes (Fig. 4 and Fig. S2). The boreal belt identifies areas with average annual temperatures below 0°C (Meybeck et al., 2013). Within this belt, we found river basins characterized by high natural discharges and a limited human presence and activity, resulting in low values of standardized human pressure.

30 River basins in the boreal belt showed negative DHPR scores, with lowest values across Canada, Europe and eastern Siberia. Northern latitude belts (mid latitude, dry and sub tropical) are known to be the most populated areas across the globe. Basins within northern latitude belts presented a wide range of natural discharges, showing fairly high values of standardized human pressure. When looking at the historic evolution of standardized human pressure on river systems, the northern mid latitude belt (i.e., corresponding to the most developed countries in the Northern hemisphere) showed DHPR values almost symmetrically

35 distributed around zero, with positive change rates across Europe and Asia and negative trends across the United States. The

highest DHPR estimates were found in river basins located within the northern dry, northern sub tropical and equatorial belts, in particular across Africa and Asia. River basins located across southern latitude belts (sub tropical, dry and mid latitudes) typically presented positive DHPR values, with slightly smaller change rates compared to northern dry, sub tropical and equatorial belts.

5   DHPR identifies critical zones where increasing trends in human pressure on river systems ~~will~~ may undermine human security and sustainable development in the near future. ~~River~~ Hot spot areas of change are represented by river basins located within the northern sub tropical and equatorial belts across Africa and Asia ~~clearly epitomize this situation~~, showing markedly positive change rates in the 1992 to 2013 period (Fig. 3, 4, Fig. S2). Future climate change scenarios and demographic projections will impact on future DHPR values. For instance, when considering African basins across the sorthern sub tropical

10 and equatorial belts, markedly positive DHPR scores are likely to be expected, with population and socio economic level predictions (Worldbank, 2017b) playing a major role than changes in natural river discharge (Roudier et al., 2014). Indeed, the highest population growth rates are predicted to be in Africa, where more than half of the global population increase (i.e., nearly 83 million people by year) will settle by 2050 (Worldbank, 2017b).

4   Discussion and Conclusions

15 Human development and riverine ecosystems intimately depend on the geographic and temporal distribution of natural river discharge (Rodriguez-Iturbe and Rinaldo, 2001; UNWWAP, 2015; Pekel et al., 2016), whose global scale pattern is primarily controlled by hydrogeomorphologic and climatic drivers. Current human ~~pressure and global sustainability levels of~~ pressures on river systems are likely to be affected by future population increases and climate change (IPCC, 2013; Worldbank, 2017b). As a consequence, managing the development of human societies and protecting fluvial ecosystems will be a significant chal-

20 lenge ~~in the near future~~ (Hoekstra and Wiedmann, 2014). The Differential Human Pressure on Rivers index (DHPR) proposed here is a simple ~~, objective and powerful tool that , by analyzing~~ tool that analyzes for the first time the temporal evolution of human pressure on river systems ~~, identifies areas where priority action needs to be taken~~. DHPR identifies hot spot areas of change, offering guidance on where implementing mitigation strategies. On account of its simplicity and the availability of spatially and temporally explicit data for its calculation, DHPR is a valuable alternative and a step forward to well acknowledged

25 and consolidated datasets mapping human pressure on terrestrial (Sanderson et al., 2002; Venter et al., 2016a) and freshwater (Vörösmarty et al., 2010) systems (see Table S1).

    We acknowledge that the proposed index presents some limitations. ~~Nightlights and river discharges are~~ Our approach defines human pressure on rivers as a basin scale cumulative effect of residing population and its economic activities on the natural river discharge at the basin outlet. In other words, we focus on (1) how many people live and act on a river basin (namely,

30 the sum of nightlights) and (2) in which way this anthropogenic effect is diluted with river discharge. Local aspects such as dams and water withdrawals for civil, industrial and irrigation purposes are not taken into account. Therefore, nightlights and river discharge are considered the sole controlling and the best representative drivers of human pressure on ~~river systems~~ rivers. Nightlights have been ~~proved~~ proven to be an effective tool monitoring human presence and activity, although featuring several

potential weaknesses (Sutton, 2003; Elvidge et al., 2010). The low resolution of nightlight sensors may cause zero values of nightlights in populated areas. The limited radiometric range may result in saturated nightlight values in urban areas (i.e., saturation effect) or in larger lit areas (i.e., blooming effect). To dampen these effects, estimates of human pressure on river systems were first standardized and then normalized. In addition, light pollution abatement strategies (Royal Astronomical

5 Society of Canada, 2017; International Dark-Sky Association, 2017) employed to reduce the artificial sky brightness and preserve world's ecosystems (de Freitas et al., 2017), can cast some doubts on nightlight values and on their evolution in time. However, these uncertainties, which should be treated with caution when analyzing small areas, are barely detectable at the basin scale here employed.

Natural river discharge, as computed from Eq. (1), is ~~simply~~ defined as a function of hydrological and geomorphological

10 variables within a river basin. One major limitation of the proposed methodology is that the variability of natural river discharges within and between years is not considered. Since the scope of the present study is to analyze and map the annual evolution of human pressure on river systems at global level, intra annual variability is out of interest. Concerning inter annual variability, future studies, focused on local scale problems and smaller areas, are planned to embed discharge variability between years and thus account for hydrological changes. Furthermore, ~~given that our focus is on natural river systems,~~ the

15 proposed approach relies on an ideal case where groundwater fluxes and anthropogenic factors (i.e., water intakes, transboundary water management and environmental flow requirements), which may potentially affect human pressure on river systems, are not taken into account. If considered, environmental flow requirements would reduce the natural river discharge (i.e., on an annual basis, 80% of natural discharge is allocated as environmental flow, Mekonnen and Hoekstra, 2016). Consequently, human pressure on river systems based on environmental flow requirements would result in higher absolute values, but change

20 rates, expressed by DHPR, would be equal to change rates of human pressure based on natural discharges. Similarly, one could account for groundwater fluxes. If considered, groundwater would potentially enhance water availability, thus resulting in lower absolute values of human pressure. However, this issue, which involves a sustainable use of groundwater resources, goes beyond the scope of the proposed analysis.

Our approach, estimating the historic evolution of human pressure on river systems, explicitly considers the connectivity and

25 the structure of the river network and provides ~~an order zero~~ a simplified information about interactions among hydrological, geomorphological and human variables within a river basin. DHPR estimates allow a spatially and temporally explicit analysis of human water interactions at the global scale. Our study identifies critical zones where the change rate of human pressure ~~will~~ may undermine human security and sustainable development in the near future. The simplicity of the proposed methodology for assessing human pressure on river systems and the ease with which it can be used to reconstruct historic series makes it

30 a powerful tool to be used independently or to be incorporated into a planning framework, targeting actions to address water threats in key areas.

Code and data availability. Nightlight data used for this article are available at NOAA Earth Observation Group (http://ngdc.noaa.gov/eog/dmsp/downloadV4composites.html), water threat data were downloaded from http://www.riverthreat.net/index.html, human footprint data

are available at doi:10.5061/dryad.052q5. Results derived from elaborations through a not opensource code developed by the authors. More information can be gathered upon e-mail request to serena.ceola@unibo.it.

Author contributions. SC, FL and AM designed the research. SC carried out the research, developed the model code and performed the simulations. SC prepared the manuscript with contributions from all co-authors.

5 *Competing interests.* The authors declare that they have no conflict of interest.

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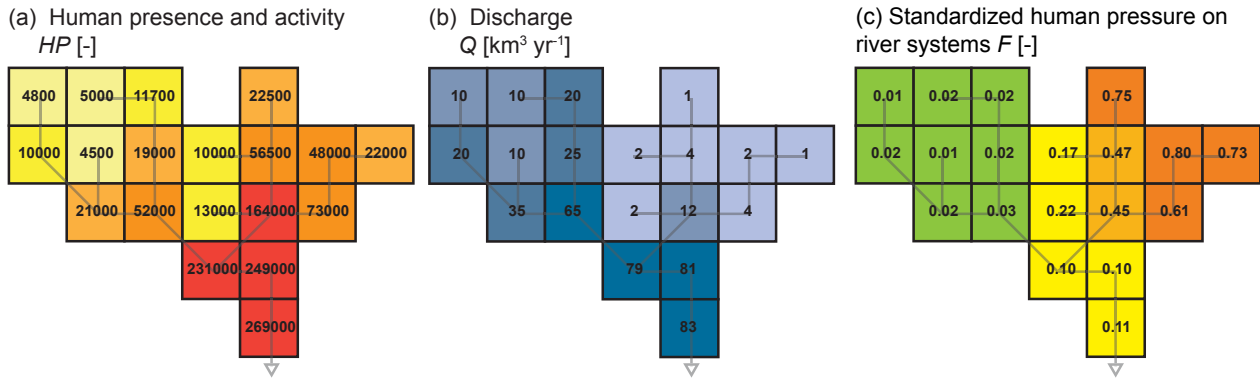
Figure 1. Estimation of human pressure on river systems by explicitly considering the topological nature of river basins. Schematic illustration of (a) cumulative human presence and activity, ~~HP~~ HP [-], calculated as routed nightlight values for each grid cell at $0.5°$ resolution, obtained from downstream propagation following flow direction paths (grey line, see Eq. 3), (b) natural river discharge, ~~Q~~ Q [km^3 yr^{-1}], obtained from downstream propagation following flow direction paths (grey line, see Eq. 1), (c) standardized human pressure on river systems, $F(t)$ [-], for each grid cell (see Eq. 2 and 4, where $\min(f_k)$=50 km^{-3} yr and $\max(f_k)$=30000 km^{-3} yr).
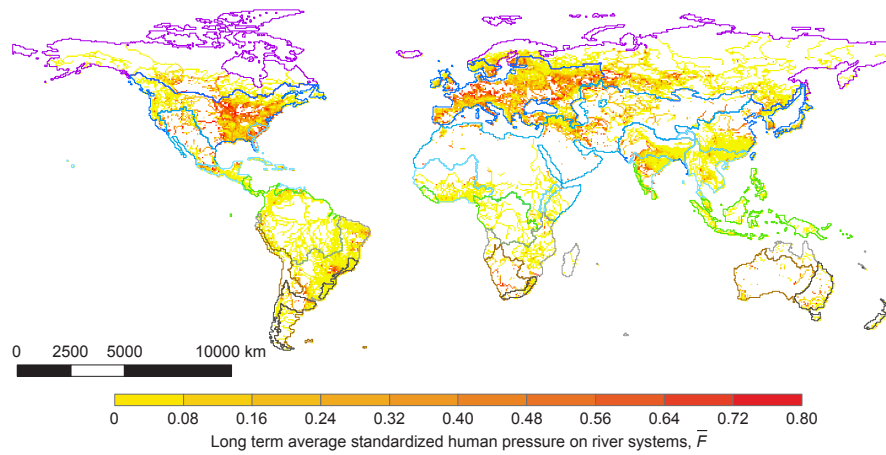
Figure 2. Global distribution of long term standardized human pressure on river systems, $\overline{F}$. Colors differentiate grid cells (20770 in total) according to levels of $\overline{F}$. Hydrobelt boundaries (Meybeck et al., 2013) are also shown (i.e., boreal in purple, northern mid latitude in dark blue, northern dry in cobalt, northern sub tropical in light blue, equatorial in green, southern sub tropical in gray, southern dry in brown, southern mid latitude belt in black).
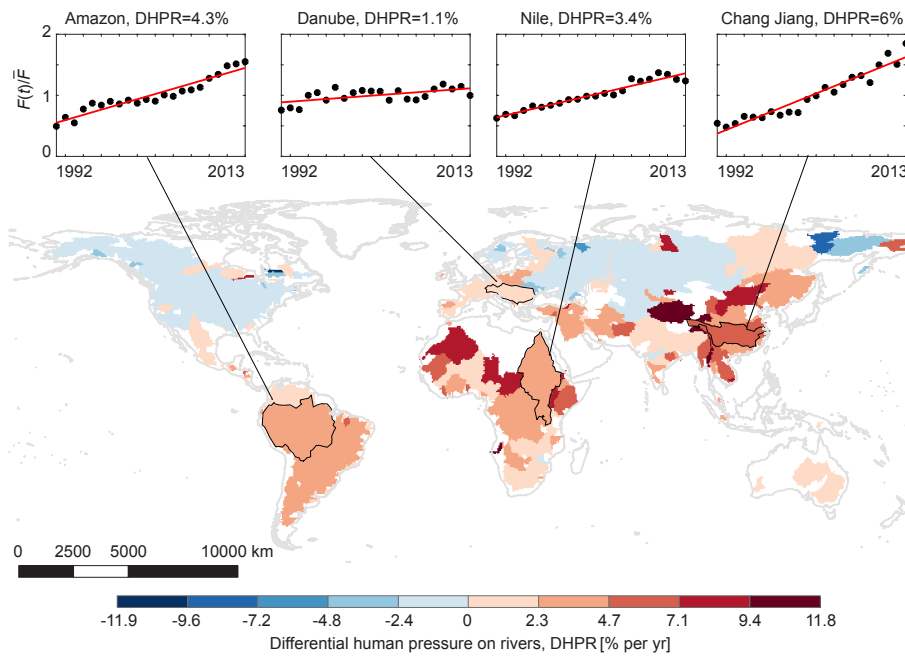
Figure 3. Global distribution of the Differential Human Pressure on Rivers index, DHPR. The map shows the relative change rate (i.e., a percentage increment or decrement) of normalized human pressure values, defined as the ratio between annual and long term average standardized human pressure on river systems, $F(t)/\overline{F}$. Colors differentiate basins (2195 in total) according to levels of DHPR. Insets show the historic evolution of normalized human pressure on river systems for Amazon, Danube, Nile and Chang Jiang river basins, where data are depicted as black dots and the red lines represent Eq.(5).
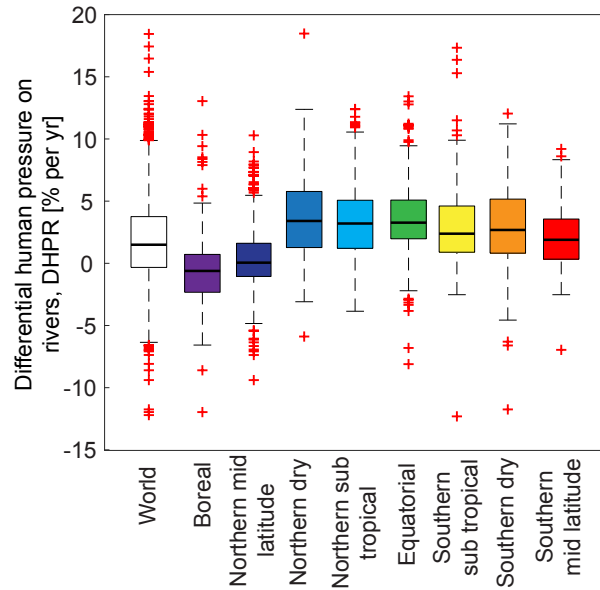
Figure 4. Regional patterns of the Differential Human Pressure on Rivers index, DHPR. Box plot statistics for DHPR grouped by hydrobelt (Meybeck et al., 2013): world (2195 basins), boreal (170 basins), northern mid latitude (800 basins), northern dry (133 basins), northern sub tropical (319 basins), equatorial (354 basins), southern sub tropical (141 basins), southern dry (84 basins), southern mid latitude (194 basins). Box plots include the median (thick black line), interquartile range (colored boxes) and whiskers (confidence interval of $\pm 2.7/\sigma$).

Table 1. Estimates of the Differential Human Pressure on Rivers index, DHPR, for 15 major river basins. Basin name, contributing area [10^6km^2], hydrobelt, hydroregion, DHPR values [% per yr], coefficient of determination R^2, and P-values for the Student's t-test are reported.

Basin Name	Area [10^6km^2]	Hydrobelt	Hydroregion	DHPR [% per yr]	R^2	P-value
Amur	1.75	Boreal	Asia (East Siberia)	3.15	0.646	<0.001
Mississippi	3.20	Northern mid latitude	North America	-0.51	0.183	0.005
Volga	1.48	Northern mid latitude	Europe	-1.00	0.221	0.003
Danube	0.79	Northern mid latitude	Europe	1.09	0.354	0.003
Rhine	0.17	Northern mid latitude	Europe	0.18	0.019	0.535
Chang Jiang	1.79	Northern mid latitude	Asia	5.97	0.927	<0.001
Ganges	1.63	Northern mid latitude	Asia	1.43	0.432	<0.001
Huang He	0.89	Northern mid latitude	Asia	4.16	0.900	<0.001
Indus	1.14	Northern mid latitude	Asia	1.05	0.554	<0.001
Niger	2.24	Northern sub tropical	Africa	2.14	0.559	<0.001
Nile	3.83	Northern dry	Africa	3.44	0.940	<0.001
Amazon	5.85	Equatorial	South America	4.24	0.909	<0.001
Zaire	3.70	Equatorial	Africa	2.94	0.676	<0.001
Parana	2.66	Southern sub tropical	South America	2.52	0.800	<0.001
Murray-Darling	1.03	Southern mid latitude	Australia	1.15	0.428	<0.001

Table A1. Estimates of long term average standardized human pressure on river systems $\overline{F}$. River basins are ranked as a decreasing function of natural river discharge, Q. The first 15 river basins are examined. Basin name, hydrobelt, hydroregion, $\overline{F}$ and quantile distribution, DHPR values [% ~~per~~ yr^{-1}per yr], coefficient of determination R^2, and P-values for the Student's ~~T-test~~ *t*-test are reported.

Basin Name	Hydrobelt	Hydroregion	$\overline{F}$	Quantile distribution	DHPR [% ~~yr^{-1}~~per yr]	R^2	P-value
Amazon	Equatorial	South America	0.0009	$< \overline{F}_{10}$	4.24	0.909	<0.001
Zaire	Equatorial	Africa	0.0008	$< \overline{F}_{10}$	2.93	0.676	<0.001
Ganges	Northern mid latitude	Asia	0.0258	$\overline{F}_{25} - \overline{F}_{50}$	1.43	0.432	<0.001
Orinoco	Equatorial	South America	0.0047	$\overline{F}_{10} - \overline{F}_{25}$	1.43	0.634	<0.001
Chang Jiang	Northern mid latitude	Asia	0.0320	$\overline{F}_{25} - \overline{F}_{50}$	5.97	0.927	<0.001
Yenisei	Boreal	Asia (West Siberia)	0.0223	$\overline{F}_{25} - \overline{F}_{50}$	-0.55	0.055	0.292
Mississippi	Northern mid latitude	North America	0.3344	$\overline{F}_{75} - \overline{F}_{90}$	-0.51	0.183	0.047
Parana	Southern sub tropical	South America	0.0603	$\overline{F}_{50} - \overline{F}_{75}$	2.52	0.800	<0.001
Irrawaddy	Northern sub tropical	Asia	0.0020	$< \overline{F}_{10}$	5.08	0.469	<0.001
Lena	Boreal	Asia (West Siberia)	0.0069	$\overline{F}_{10} - \overline{F}_{25}$	0.64	0.046	0.337
Mekong	Northern sub tropical	Asia	0.0098	$\overline{F}_{10} - \overline{F}_{25}$	6.75	0.708	<0.001
Ob	Boreal	Asia (West Siberia)	0.1124	$\overline{F}_{50} - \overline{F}_{75}$	-0.35	0.029	0.449
Tocantins	Equatorial	South America	0.0046	$\overline{F}_{10} - \overline{F}_{25}$	3.78	0.795	<0.001
St. Lawrence	Northern mid latitude	North America	0.2925	$\overline{F}_{75} - \overline{F}_{90}$	-1.60	0.738	<0.001
Amur	Boreal	Asia (East Siberia)	0.0544	$\overline{F}_{25} - \overline{F}_{50}$	3.15	0.646	<0.001

Table A2. Estimates of long term average standardized human pressure on river systems $\overline{F}$. River basins are ranked as a decreasing function of human presence and activity, HP. The first 15 river basins are examined. Basin name, hydrobelt, hydroregion, $\overline{F}$ and quantile distribution, DHPR values [% ~~per~~ yr^{-1}], coefficient of determination R^2, and P-values for the Student's ~~T-test~~ *t*-test are reported.

Basin Name	Hydrobelt	Hydroregion	$\overline{F}$	Quantile distribution	DHPR [% ~~yr^{-1}~~ per yr]	R^2	P-value
Mississippi	Northern mid latitude	North America	0.3344	$\overline{F}_{75} - \overline{F}_{90}$	-0.51	0.183	0.047
St. Lawrence	Northern mid latitude	North America	0.2924	$\overline{F}_{75} - \overline{F}_{90}$	-1.60	0.738	<0.001
Volga	Northern mid latitude	Europe	0.3196	$\overline{F}_{75} - \overline{F}_{90}$	-1.00	0.221	0.027
Danube	Northern mid latitude	Europe	0.3171	$\overline{F}_{75} - \overline{F}_{90}$	1.09	0.345	0.003
Ob	Boreal	Asia (West Siberia)	0.1124	$\overline{F}_{50} - \overline{F}_{75}$	-.035	0.029	0.449
Nelson	Boreal	North America	0.4735	$>\overline{F}_{90}$	-1.26	0.244	0.019
Rhine	Northern mid latitude	Europe	0.5508	$>\overline{F}_{90}$	0.18	0.019	0.535
Indus	Northern mid latitude	Asia	0.2385	$\overline{F}_{75} - \overline{F}_{90}$	1.05	0.554	<0.001
Parana	Southern sub tropical	South America	0.0603	$\overline{F}_{50} - \overline{F}_{75}$	2.52	0.800	<0.001
Ganges	Northern mid latitude	Asia	0.0285	$\overline{F}_{25} - \overline{F}_{50}$	1.43	0.432	<0.001
Chang Jiang	Northern mid latitude	Asia	0.0320	$\overline{F}_{25} - \overline{F}_{50}$	5.97	0.927	<0.001
Huang He	Northern mid latitude	Asia	0.5093	$>\overline{F}_{90}$	4.16	0.900	<0.001
Po	Northern mid latitude	Europe	0.4063	$\overline{F}_{75} - \overline{F}_{90}$	1.09	0.784	<0.001
Dnepr	Northern mid latitude	Europe	0.4527	$>\overline{F}_{90}$	-1.62	0.201	0.036
Shatt el Arab	Northern dry	Asia (Central Asia)	0.2039	$\overline{F}_{75} - \overline{F}_{90}$	2.71	0.799	<0.001