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A spatial evaluation of global wildfire-water risks to human and natural systems

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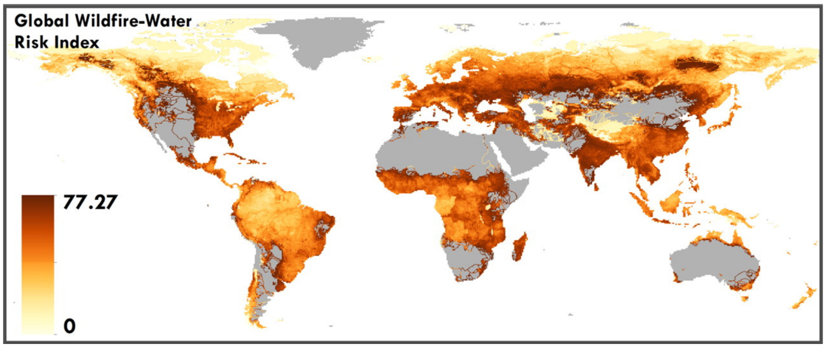
HIGHLIGHTS

- Severe wildfires may endanger the water supply of human and natural communities.
- We created a global index to assess wildfire risks to water security.
- We used the DPSIR framework to select and aggregate 33 risk indicators into one index.
- Beyond post-fire hazards, potential impacts and resilience capacities drive the global wildfire-water risk.
- Wildfire risk to water security can occur globally but may be particularly acute in water-insecure countries.

GRAPHICAL ABSTRACT



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ABSTRACT

The large mediatic coverage of recent massive wildfires across the world has emphasized the vulnerability of freshwater resources. The extensive hydrogeomorphic effects from a wildfire can impair the ability of watersheds to provide safe drinking water to downstream communities and high-quality water to maintain riverine ecosystem health. Safeguarding water use for human activities and ecosystems is required for sustainable development; however, no global assessment of wildfire impacts on water supply is currently available. Here, we provide the first global evaluation of wildfire risks to water security, in the form of a spatially explicit index. We adapted the Driving forces-Pressure-State-Impact-Response risk analysis framework to select a comprehensive set of indicators of fire activity and water availability, which we then aggregated to a single index of wildfire-water risk using a simple additive weighted model. Our results show that water security in many regions of the world is potentially vulnerable, regardless of socio-economic status. However, in developing countries, a critical component of the risk is the lack of socio-economic capability to respond to disasters. Our work highlights the importance of addressing wildfire-induced risks in the development of water security policies; the geographic differences in the components of the overall risk could help adapting those policies to different regional contexts.

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1. Introduction

Ensuring water security, which is defined as the assurance of sufficient and safe freshwater resources for human development and ecosystem functioning, has long been a challenge in developing countries (United Nations, 2005), and is a growing issue in more developed countries as population pressures increase consumption and pollution (Norman et al., 2012). Despite measurable improvements within the past decades, water insecurity still threatens or affects many countries. For instance, >2-billion people do not have access to an improved source of water (United Nations, 2016; Gain et al., 2016). Many of the critical issues are due to water pollution, diversion, or depletion (Hoekstra and Mekonnen, 2012; Meybeck, 2003; Schwarzenbach et al., 2010). Complex relationships among social stability, ecosystem health, and freshwater availability have been recognised, all of which condition water security (Dodds et al., 2013; Padowski et al., 2015; Rockström, 2009). These relationships may be modified or enhanced by the occurrence of extreme natural disturbances (Grigg, 2003; Huppert and Sparks, 2006), thereby increasing the challenge of maintaining or achieving water security (Hall and Borgomeo, 2013; Srinivasan et al., 2012).

Recent catastrophic wildfires, characterized by extreme fire behaviour leading to life and infrastructure losses (Cruz et al., 2012), in the USA (e.g. California and Colorado), Canada, and Chile have drawn attention to the nexus among fire, water, and societies (Martin, 2016). These natural disasters have increased interest in the wide range of consequences a severe and large wildfire can have on the reliability of surface freshwater resources (Emelko et al., 2011; Kinoshita et al., 2016). The hydrogeomorphic effects of wildfires can be numerous, spatially extensive, and long-lasting. These effects include increased annual water yields and peak flows, shifts in the timing of runoff due to earlier snowmelt, and decreased water quality due to high sediment and nutrient loads (Shakesby and Doerr, 2006). Bladon et al. (2008) and Emelko et al. (2015) noted significantly higher concentration of trace elements, phosphorus and organic carbon in the water downstream of severely burned sites, persisting after several years. In the USA, Hallema et al. (2016) attributed to wildfire a +219% increase in annual water yield in a watershed in Arizona, while Moody and Martin (2001b) documented a 200-fold increase in erosion rates in two watersheds in Colorado. Conedera et al. (2003) recorded a 200-year flood in a mountain catchment in Switzerland induced by a 10-year precipitation event, which are otherwise observed for a 40-year precipitation event in an unburned basin and with much higher flow velocity. Post-fire hydrogeomorphic hazards may consequently expose water resources to drastic quality and quantity changes that can impair downstream water supply of human and natural communities.

These post-fire impacts on the downstream water supply can result in substantial economic costs (Emelko et al., 2011; Emelko and Sham, 2014), and adversely affect human and environmental health (Finlay et al., 2012; Writer and Murphy, 2012). Greater erosion rates in burned watershed have increased sedimentation in reservoirs regulating drinking-water provision (Moody and Martin, 2004; Smith et al., 2011), thereby reducing their storage capacity and their lifespan. The increased concentration of dissolved organic carbon, often documented, pose serious issues for water treatability as it favours the formation of carcinogenic disinfection by-products (Writer et al., 2014). Other hazardous chemicals, such as lead or arsenic, can accumulate downstream in quantities far greater than what is prescribed for drinking-water quality by the World Health Organization (Tecle and Neary, 2015). The trophic chain of riverine and lacustrine ecosystems can be highly disturbed by changes in turbidity and chemical element concentration (Tobergte and Curtis, 2016) leading to decrease in ecosystem health with consequences on fisheries and recreational use of water (Tecle and Neary, 2015). The water security of downstream human and natural communities may, therefore, be threatened, making them vulnerable to risk from wildfire (hereafter 'wildfire-water risk' [WWR]) (Bladon et al., 2014; Robinne et al., 2016; Thompson et al., 2013). Seven years after the 2002 Hayman Fire in Colorado, Denver Water had to invest $30 million to dredge the city's reservoirs, which was filled with sediments transported from burned areas (Denver Water, 2010). In 2014, the Sydney Catchment Authority, in Australia, had to shut down a water treatment plant after heavy water contamination by ashes (Santín et al., 2015). As an emerging risk to coupled human-water systems, the WWR has been gaining in interest for the past decade. However, the threat it represents to global water security remains to be understood in a context of planetary change (Bogardi et al., 2012), in which extreme weather events, such as droughts and floods (Mann et al., 2017) are predicted to become increasingly common.

Global composite indices are commonly used in water security assessment (Garrick and Hall, 2014; Vörösmarty et al., 2010), risk analysis (De Bono and Mora, 2014; Dilley et al., 2005; Peduzzi et al., 2009), and other diverse environmental questions (Freudenberger et al., 2012; Halpern et al., 2009). Composite indices are efficient tools to explore complex environmental processes and to convey high-value information to policy-makers in an easily understandable manner (Gregory et al., 2013). They also help detect temporal and spatial trends in the evolution of a process, making them valuable to monitor policies effectiveness (OECD, 2008). However, a robust composite index requires a well-structured analytical framework. The Driving forces-Pressure-State-Impact-Responses (DPSIR) framework (EEA, 1999) simplifies complex causal relations between human and natural systems at several spatial scales (Bitterman et al., 2016; Freudenberger et al., 2010). It has been successfully applied to questions related to risk evaluation, water resources management, biodiversity protection, and economics (Freudenberger et al., 2012; Halpern et al., 2009). Meybeck (2003) contends the DPSIR framework as an appropriate tool for the analysis of global issues impacting freshwater quality and availability. The novelty of the WWR and its inherent complexity make it a good candidate for a DPSIR analysis. This framework is considered a problem structuring method that can help organising the numerous natural and social processes involved in the characterization of the risk and thus provide a tool to develop targeted policies (Gregory et al., 2013).

The present study adapts the DPSIR framework to produce the first global-scale assessment of the wildfire risks to water security. Our objective is threefold: 1) develop a reference WWR spatial analysis framework at a global scale, 2) understand the current geography of the WWR according to the different criteria involved, and 3) raise awareness of WWR issues to global water security challenges. To do so, we demonstrate the benefit of the DPSIR risk-based framework to creating a spatially explicit index. This index is then used to produce a global map showing the geography of the risk. We finally discuss the importance of our approach to the understanding of wildfire risks to water security and the questions posed by future global changes.

2. Data and methods

2.1. Data

For clarity, we present hereafter the 33 global datasets we used according to the five Drivers-Pressure-State-State-Impact categories, and we briefly explain their use as indicators (Table 1). Although our application of the DPSIR framework deviates from that from the original by EEA (1999), our adaptation of this approach remains similar to numerous other studies (Maxim et al., 2009). As no specific data depository representing the diversity of post-fire issues is currently available, we relied on the literature to select a large panel of datasets, available free of charge, to represent this diversity.

2.1.1. Driving forces

The driving forces are those elements that trigger a chain of cascading events leading to the appearance of an environmental problem. For the WWR, post-fire effects are triggered by the combination of large and

Table 1
List of the variables used to compute the WWR index. (I) specifies indicators whose values were inverted.

Name	DPSIR	Unit	Temporal coverage	Spatial resolution	Source	Proxy
Monthly mean Build-Up Index	D	Unitless	1990–2010	0.5° × 2/3°	Global Fire Weather Database (GWFED)	Potential for greater depth of burn and vegetation combustion
Fire counts	D	Thermal anomalies/yr	2001–2010	0.5° × 0.5°	NASA Global Monthly Fire Product (MCD14ML)	Potential for fire susceptibility and soil impoverishment
Soil macrofauna diversity	D	# groups	2015	0.008° × 0.008°	European Commission JRC	Potential for higher soil moisture and lower ground fuels, thus limiting fire ignition and spread (I)
Human appropriation of net primary productivity	D	g C/m^2/yr	1995	0.25° × 0.25°	NASA SEDAC	Potential for human ignition
Lightning flash density	D	Flashes/km^2/yr	1995–2000	0.5° × 0.5°	NASA GHRC	Potential for natural ignition
Max 1-day precipitation	D	mm	1979–2011	2° × 2.5°	CLIMDEX NCEP2 Reanalysis	Potential for heavy rainstorm
Global topography	D	Unitless	2007–2012	0.008° × 0.008°	SCALA project	Potential for dangerous fire behaviour, flash flooding, and debris flow
Topsoil bulk density	P	kg/dm^3	2000	0.05° × 0.05°	NASA HWSD	Potential for reduced post-fire infiltration
Topsoil sand content	P	% weight	2000	0.05° × 0.05°	NASA HWSD	Potential for hydrophobicity
Sediment deposit thickness	P	Meters	1900–2015	0.008° × 0.008°	University of Arizona, USA	Potential for changes in post-fire turbidity and solid transport
Erodibility factor K	P	t ha h/ha/MJ/mm	1995–2009	0.008° × 0.008°	GTOPO-ETOPO-Max Planck Institute for Meteorology, Germany	Potential for postfire erosion susceptibility
Soil moisture holding capacity	P	mm	1995	0.08° × 0.08°	IGBP_DIS	Potential for changes in soil water storage
Smoke deposition PM 2.5	P	μg/m^3	1997–2006	2° × 2.5°	University of Tasmania, Australia	Potential for water pollution from smoke deposition
Annual mean runoff	P	mm/yr	1950–2000	0.5° × 0.5°	GWSP	Potential for post-fire effects accumulation (I)
Soil fungal diversity	S	# of taxons	1960–1990	0.33° × 0.33°	University of Tartu, Estonia	Potential for changes in soil stability and vegetation regrowth
Above ground biomass (carbon)	S	mg/ha	2000–2011	0.01° × 0.01°	GeoCarbon project	Potential for the production of labile combustion by-products
Topsoil organic carbon content	S	% weight	2000	0.05° × 0.05°	NASA HWSD	Potential for the production of labile combustion by-products
Soil phosphorus concentration	S	% weight	Multiple	0.08° × 0.08°	GSDE	Potential for the production of labile combustion by-products
Soil nitrogen concentration	S	g/m^2	1995	0.08° × 0.08°	IGBP_DIS	Potential for the production of labile combustion by-products
Yearly mean snow-water equivalent	S	mm	2000–2010	0.25° × 0.25°	NASA GLDAS	Potential for changes in flow seasonality
Flooded area fraction (100 years return interval)	S	% per area	1960–2013	0.25° × 0.25°	University of Tokyo, Japan	Potential for catastrophic floods
Forest age	S	Age of dominant PFT	Multiple	0.5° × 0.5°	Montana State University (Unpublished work), USA	Potential for changes in large woody debris production
Environmental water requirements	I	% total discharge	1961–1990	0.3° × 0.3°	IWMI	Potential for water supply contamination
Freshwater biodiversity	I	Species richness	1994–2012	(Vector)	Zoological Society of London, England	Potential for adverse effects of freshwater ecosystems
Domestic water withdrawal	I	m^3/hab/yr	1900–2010	0.008° × 0.008°	Aquastat-LANDSCAN	Potential for water supply contamination
Lake density	I	# lakes/km^2 (weighted by size)	1992–1998	(Vector)	WWF-GWLD	Potential for water supply contamination (I)
Sediment trapping by large dams	I	% land to ocean flux	2003	0.5° × 0.5°	GWSP	Potential for the reduction of dams' lifetime
Water stress index	I	km^3	1995–2002	0.5° × 0.5°	WWRII-UNH	Potential for water supply contamination
Gross Domestic Product per cap.	R	Current US$	2016	–	World Bank	Potential for risk management
Investment benefit factor	R	Unitless	2010	0.3°×0.3°	Riverthreat.net	Potential for resilience
Healthcare access	R	# of hospital beds	2012	–	World Development Indicators	Potential access to health care
Risk education capacity	R	# of pupils	2012	–	UNESCO	Potential for prevention
Travel time	R	# hours	2008	0.008° × 0.008°	European Commission JRC	Potential accessibility for intervention and restoration

intense wildfire activity, high biomass load, extreme precipitation or snowmelt, and a steep terrain. We included seven variables in the analysis of the Driving Forces category.

We used the monthly average of the Build-Up Index (BUI) data (1998–2014 TRMM-3B42 version) from the Global Fire Weather Database (Field et al., 2015) as a proxy for fire severity. The BUI, based on the Canadian Fire Weather Index (FWI) System, is related to the amount of fuel available for combustion. The FWI System is a weather-based system and does not explicitly include vegetation type, structure and associated biomass loading in the calculation. Fire severity essentially affects soil functioning—a critical determinant of hillslope runoff generation (Neary et al., 2009)—by reducing the amount of above- and below-ground organic matter and exposes the soil to the erosive forces of rain, favoring excessive high-velocity runoff (Doerr et al., 2000). To approximate fire frequency, we used an aggregated sum of the yearly NASA MODIS fire counts for the period 2000–2010 (Giglio, 2007), with higher values having a stronger negative effect. In addition, we integrated data on soil macrofauna diversity (Orgiazzi et al., 2015) (e.g. earthworms, arthropods, ants, and moles). According to recent studies, soil engineering capacities of macrofauna may limit fire occurrence and impacts (Hayward et al., 2016; Henig-Sever et al., 2001) and act as a buffer to post-fire runoff (Cerdà and Doerr, 2010).

Fire activity across the world is highly correlated—both positively or negatively—with human pressure on landscapes (Bistinas et al., 2013). We used the human appropriation of net primary productivity (HANPP) (Imhoff and Bounoua, 2006) as a proxy for human ignition capacity. The data, provided by the Socioeconomic Data and Application Center, is the ratio of available NPP to the human demand of NPP per capita, according to local water consumption patterns. Fire ignitions also naturally occur through lightning activity. Lightning-induced fires have an important ecological role (Ramos-Neto and Pivello, 2000) and they usually display different spatial and seasonal patterns compared to human-caused fires (Müller et al., 2013; Vazquez and Moreno, 1998). They can also account for the largest burned areas in flammable forested ecosystems (Gralewicz et al., 2012). We used lightning flash density data on natural lands derived from the LIS and OTD sensors provided by the NASA Global Hydrology Resource Center (Cecil et al., 2014), although this data does not represent the density of ground strikes per se but the density of flashes.

Post-fire precipitation intensity is a paramount factor driving the occurrence and magnitude of post-fire hydrogeomorphic effects (Moody and Martin, 2001a). Heavy precipitation events following large and severe wildfires can trigger destructive flash floods with unusually high streamflow and debris loads leading to catastrophic effects on downstream infrastructures (Jordan, 2015) and water quality (Neary and Tecle, 2015). To represent the occurrence of extreme precipitation, we used the maximum one-day precipitation amount from the CLIMDEX NCEP2 reanalysis data (Sillmann et al., 2013) created by the Expert Team on Climate Change Detection and Indices (Zhang et al., 2011). Important post-fire hydrogeomorphic effects described in the literature usually happen in rugged terrains (Miller et al., 2011), where steep slopes are common, which therefore allows for the generation of frequent runoff-erosion events. To account for the effect of terrain ruggedness in our framework, we used a global physiographic landform layer derived from the SRTM mission (Drăguţ and Eisank, 2012).

2.1.2. Pressure

Indicators of the Pressure category of the DPSIR framework are proxies to the first order effects of wildfires on hydrosystems. In other words, these indicators inform on the direct hydrogeomorphic changes caused by the driving forces of fire severity and area burned that can eventually lead to downstream impacts. We included seven indicators in the estimate of the Pressure category.

The potential for an increase in the frequency and intensity of post-fire erosion-runoff events with potential impacts on water quality and quantity was approximated with soil variables from various global datasets (Batjes et al., 2009; Shangguan et al., 2014). Topsoil bulk density gives an idea of pre-fire soil structure and wettability (Neary et al., 2009), whereas topsoil sand content has been reported many times as a vector of post-fire hydrophobicity (DeBano, 2000). Data on sediment deposit thickness (Pelletier et al., 2016) was added to underline the importance of adsorption processes between solid particles and many chemicals that therefore use sediments as a medium to accumulate downstream. We also retrieved soil moisture holding capacities from the IGBP soil database (Global Soil Data Task, 2014) to account for the potential excess runoff. To account for the often-observed reduction in post-fire soil infiltration (Certini, 2005; USDA, 2005), we considered the hydrologic effect more deleterious in areas of higher pre-fire moisture. We also included the erodibility factor K from a global RUSLE model (Naipal et al., 2015) to get a sense of preferential erosion areas.

As the deposition of smoke on surface freshwaters is believed to impact water quality (Spencer et al., 2003), we integrated this aspect using global smoke deposition estimates of 2.5 μm particulate matter derived from satellite observations of wildfire smoke emissions and global air mass modelling (Johnston et al., 2015). The mean annual runoff was retrieved from the Global Water System Project digital water atlas (GWSP, 2008) and was used to account for areas where post-fire overland flow is likely to enhance existing runoff values.

2.1.3. State

State indicators represent changes in quality and quantity of a phenomenon as a function of biotic and abiotic pressures. Applied to the WWR, those indicators approximate induced post-fire hazards as the various effects of post-fire hydrogeomorphic changes on nutrient concentration, flood occurrence, earlier peak flows, coarse woody debris flows, and ecosystems water retention capacities. We used eight indicators to represent the State category.

Frequent and severe wildfires can seriously deteriorate the soil microbiota (Prendergast-Miller et al., 2017), thereby increasing nutrients availability for leaching and soil instability after wildfire, as well as limiting vegetation recovery. We used a global representation of soil fungal diversity (Tedersoo et al., 2014) to account for this potential change in soil biotic capacities. Higher levels of organic matter, represented by vegetation, litter, and humus in the soil might favour the availability of labile chemical compounds transported by post-fire leaching and runoff, potentially leading to water treatment challenges. We retrieved aboveground biomass data from the Geocarbon project (Avitabile et al., 2014) and we used several global soil datasets (Table 1) to account for belowground organic carbon, soil nitrogen, and soil phosphorus concentration. As most of the fire effects on soils are detectable in the first centimetres of the soil profile (González-Pérez et al., 2004), we only used topsoil information (0–30 cm) where available.

Wildfires, as disturbance agents of the hydrological cycle, favour the occurrence of floods triggered by storms or snowmelt (Rulli and Rosso, 2007; Seibert et al., 2010). To account for those potential changes, we used snow-water equivalent data from the Global Land Data Assimilation System (GLDAS) (Rodell et al., 2004) and the flooded area fraction derived from a global 100-year river floods vulnerability model (Tanoue et al., 2016). Post-fire flash floods also favour coarse woody debris recruitment, with a surge of material directly after the fire. Woody debris flows are themselves influenced by forest age, as older forests tend to produce more debris. We accounted for this hazard using global forest age data (Poulter et al., In prep.).

2.1.4. Impacts

Indicators addressing impacts translate the effects of pressures and consequent changes on highly valued resource critical for the functioning of human and natural components of the system. In the WWR context, upstream hydrogeomorphic pressures cause changes to water quality and quantity, thereby threatening water supply capacity to downstream human communities and ecosystems. We used six indicators to represent these impacts.

As wildfires affect water flows and chemical balance, freshwater ecosystems might be exposed to disruptions of their environmental flows (Dahm et al., 2015). We used the global estimation of environmental water requirements developed by Smakhtin et al. (2004) based on the ratio of available water and variability of runoff. Closely associated with environmental flows, freshwater biodiversity can be particularly sensitive to post-fire changes in water characteristics (Bixby et al., 2015), and we thus integrated a global estimation of freshwater biodiversity (Collen et al., 2014).

Impacts of wildfires to the water supply of human communities is a growing concern (Bladon et al., 2008; Hohner et al., 2017). We integrated several indicators approximating these effects on freshwater resources. We calculated domestic water withdrawal based on the ratio of water withdrawal per capita (FAO, 2016) to average population density derived from 2000 to 2013 LANDSCAN data (UT-Battelle LLC, 2013). We also computed the global density of lakes using the Global Lakes and Wetlands Database levels 1 and 2 (Lehner and Döll, 2004). Post-fire sediment exports can lead to higher sedimentation rates in reservoirs, a concerning effect that can reduce reservoir life expectancy (Moody and Martin, 2004). This impact was represented by the use of potential sediment trapping data by large dams (Vörösmarty et al., 2010). We finally included the relative water stress index, as the ratio of total human water consumption to renewable water resources (Vörösmarty, 2000). This last indicator informed on areas experiencing chronical water supply disruption that might be aggravated by cumulative impacts to freshwater resources from burned areas.

2.1.5. Response

The Response category illustrates crisis management options, as well as tools and methods for risk management that are available to societies and their capacities to deploy them. Applied to the WWR, improvements in fire prevention, firefighting techniques, post-fire watershed restoration, and post-fire risk mitigation seem to be adequate responses. The Response, therefore, defines the level of resiliency of a socio-hydrosystem to the wildfire-water risk. The absence of global data on wildfire management expenditures precludes the creation of the indicators identified in the DPSIR diagram. We used diverse datasets, five in total, to approximate this capacity.

We used Gross Domestic Product per capita (The World Bank, 2016) as the best way to represent risk management capacity (Lerner-Lam, 2007). We also used Investment Benefit Factor data (Vörösmarty et al., 2010) as a proxy to the likelihood of society to maintain access to water following post-fire hazard occurrence. The number of hospital beds per 1000 people was used as a proxy for healthcare access (Horev et al., 2004) and the ratio of pupils to total population as a proxy for risk education capacities (Izadkhah and Hosseini, 2005). We considered those both indicators as critical aspects of social resilience to disaster. Data were retrieved from the Global Assessment Report on Disaster Risk Reduction (De Bono and Mora, 2014). Finally, we incorporated travel time data (Nelson, 2008) to account for the importance of the transportation network in response to a disaster, which here can be the capacity to fight a fire or site accessibility for restoration.

2.2. Indicator development

The DPSIR framework offers both a widely validated environmental risk analysis method and a flexible design as to the potential range of indicators included and thus the complexity of the studied process (Tscherning et al., 2012). Based on known cause-and-effects relationships, this framework provides a logical tool to identify the different variables involved in the evaluation of the post-fire hydrological risk, as well as a method to sort them into categories interconnected by environmental dynamics (Maxim et al., 2009; Niemeijer and de Groot, 2008). Therefore, fitting our WWR approach to the DPSIR framework was the first critical step (Fig. 1). The DPSIR logic is driven by the significance of indicators, usually based on experts' opinion, in explaining the system under study (Bitterman et al., 2016). It means that several identified indicators may not be part of the final index if data to represent them are unavailable.

We used datasets that were publicly available or easily obtained and converted them all to the same raster format. Data were processed in ArcGIS 10.1(Environmental Systems Research Institute, 2012) to produce a set of 34 indicators at 0.25 × 0.25° spatial resolution in the WGS84 coordinate system. We did not keep small islands, Greenland, Antarctica, and areas with a runoff <10 mm/year in the analysis thus applied on a final pool of 19,235 pixels. We adjusted (i.e., multiplied) the values of each raster data according to their probability of experiencing a fire (Moritz et al., 2012), for $p > 0.2$. This way, we emphasised the information contained in areas of higher probability as a potential source of post-fire hydrogeomorphic hazards or a preferential sink of exposure to post-fire hydrogeomorphic hazards. We then inverted the values of three variables—soil macrofauna, global runoff, and lake density—with a linear transformation, thus accounting for the inverse relationship between these indicators and the inferred level of risk.

To simulate the propagation and the accumulation of those hazards downstream of drainage basins, we applied a routing function to all indicators in the D, P, and S categories. These indicators represented material that can be mobilised after a fire (e.g., runoff, debris, sediments, or nutrients) as well as processes and phenomena that mobilise this material (e.g., snowmelt, landslide). Based on a topological drainage network, upstream pixel values were added iteratively to downstream pixel values along a flow path (i.e., a network of contiguous pixels) from the source to the basin outlet, thereby mimicking downstream accumulation over the whole area. We applied the *accuflux* function available in PCRaster-Python Extension (Karssenberg et al., 2010; van Rossum, 1995) onto the Dominant River Tracing network (Wu et al., 2012) for macroscale hydrological modelling. I and R categories were not routed.

Layers resulting from downstream-routing were then normalized (i.e. divided) by the global hydrologic discharge, which simply is the result of downstream-routing applied to the runoff (Vörösmarty et al., 2010). This step acknowledges the adage ‘the solution to pollution is dilution’, which implies that the adverse effect of pollutant concentration is countered by higher volume of water available for dilution. We transformed routed and non-routed indicators using a base-10 logarithm function to obtain a standardized scale of values across all categories and to better account for contributing areas in the final index. We grouped these indicators according to their DPSIR category (Table 1), and we applied a principal component analysis (PCA) to each category, thereby collapsing the information spread across many indicators (see Appendix B). We only retained the first component of each category to create five global indicators, one for each category. We finally normalized the Response global indicator by the GDP per capita provided by the World Bank (The World Bank, 2016), which penalised the locations with lower GDP values during the aggregation process.

We used Insensa-GIS (Biber et al., 2011), a software designed for the creation and verification of spatially-explicit composite indices, to create our WWR index. We first standardized our global indicators on a 0–100 scale using the following formula following notation standards prescribed by the OECD (2008):

$$I_q\left(\frac{x_q - x_{q\ \min}}{x_{q\ \max} - x_{q\ \min}}\right)\cdot 100$$

where I_q is a standardized global indicator and x_q the pixel values of the global indicator standardization is applied to. Then, we computed a composite indicator CI following a linear (i.e. additive) weighted aggregation method:

$$CI = \sum (I_{q,c} \cdot w_{q,c})$$

with $I_{q,c}$ being the global indicator for each DPSIR category and $w_{q,c}$ the weight attributed to the global indicator. As proposed by Bitterman et al. (2016), the weights of each global indicator were assigned as a function of the number of in-out connections between categories (Table 2), as displayed in the DPSIR flowchart (Fig. S1); categories with a higher number of connections were de facto attributed a higher weight. Finally, we performed a sensitivity analysis of the final WWR index, although limited for this study to jackknifing and low–high case scenarios (but see Freudenberger et al., 2013, 2012; Robinne et al., 2016), presented in Appendix C.

We produced a global map of the resulting composite index (Fig. 2). After a general evaluation of the global risk pattern, an analysis was carried out using the global hydrobelt dataset created by Meybeck et al. (2013) to get a better sense of the WWR's regional patterns. Hydrobelts are defined as “global-scale delineations of the continental landmass

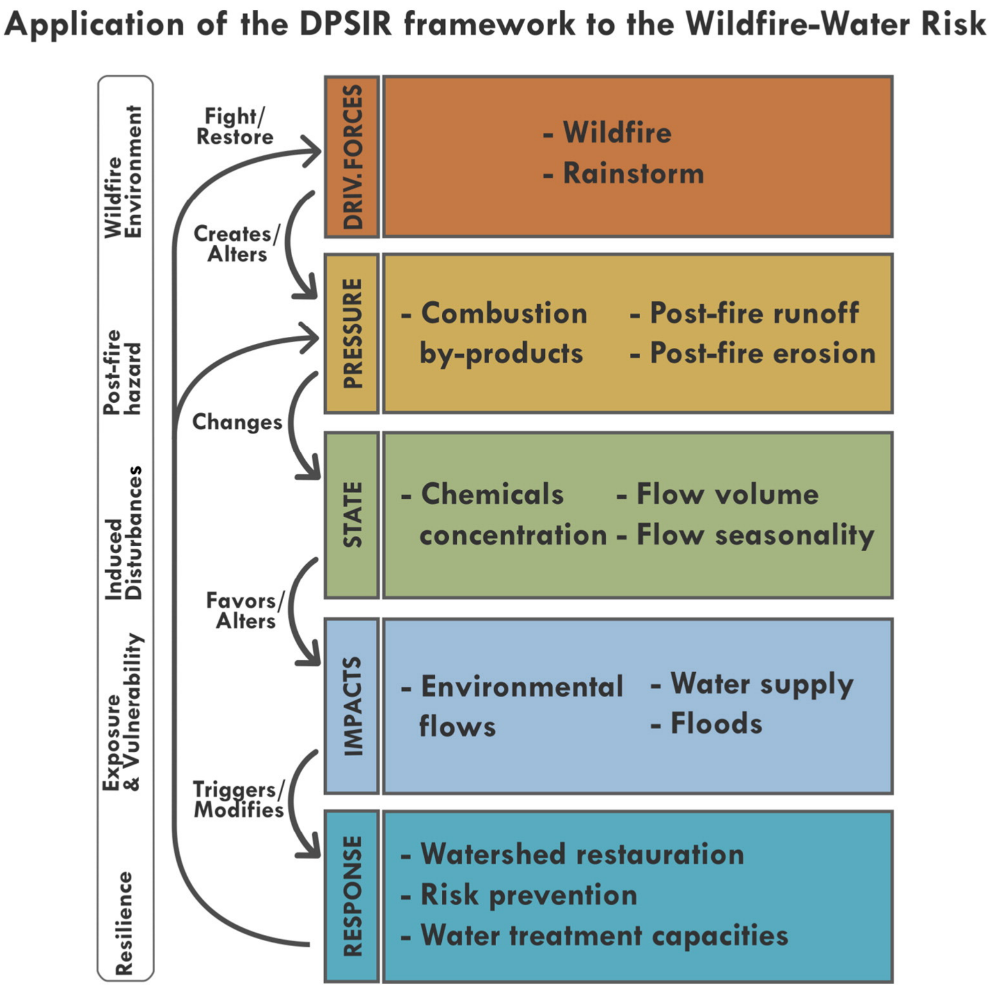

Fig. 1. Simplified version of the Driving Forces-Pressure-State-Impact-Response framework applied to the wildfire-water risk analysis (see Appendix A for a complete version). Each DPSIR category was paired with aspects of risk management: the wildfire environment as driving forces, potential post-fire hazards as pressures, induced post-fire disturbances triggered by post-fire hazards as states, exposure and vulnerability to those induced disturbances as impacts, and resilience capacities as the response. We applied an identical color scheme to symbolize each DPSIR category in the following figures. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

into homogeneous hydrological regions", based on the merging of non-glaciated continental river basins showing a similar hydroclimatic regime (Meybeck et al., 2013). We extracted the weighted raster values of our global indicators within each hydrobelt to examine the individual contribution of each DPSIR category to the final index scores, and compared the controls of the risk within and between hydrobelts. We applied the same extraction method to the watersheds of 16 arbitrarily selected cities whose surroundings are regularly affected by wildfires. Those cities represented a diversified sample of environmental conditions (human and natural) found around the world. Watershed boundaries were derived from the Aqueduct 2.1 dataset developed by the World Resource Institute (Gassert et al., 2014).

Table 2
Number and direction of linkages among DPSIR categories and their respective final weights.

Category	Links in	Links out	Total links	Weight
Drivers	4	15	19	0.16
Pressure	15	14	29	0.25
State	12	12	24	0.20
Impact	12	14	26	0.22
Response	14	6	20	0.17

3. Results

Values of the global composite index of the wildfire-water risk range from 0.25 to 77.27, with a mean of 18.11 and a standard deviation of 12. A closer look indicates that ~3.5% (Score ≥ 40) of the global area is at a substantially greater risk from wildfire impacts on water than other regions of the world. However, approximately 45.5% of the terrestrial area of the earth is at a moderate risk (Score = 20–40), while ~51% is at a relatively low risk (Score < 20). Greater risk scores are mostly found in the continental parts of the Northern hemisphere around the Great Plains of North America and Interior Alaska; Central Asia; North-Eastern China; Mongolia; in the Yakutsk basin in eastern Russia (Fig. 3). The Iberian Peninsula, Eastern Europe and Anatolia, and a few clusters in Africa, South America, India and Australia show greater wildfire-water risk values. The index shows that moderate risk is common at tropical and intertropical latitudes, as well as in Eastern North-America, in western and northern Europe, and the large continental plains of Eurasia. The majority of low risk scores are found in the Equatorial belt, especially in the Amazonian forest, with scores between 10 and 20; in large portions of the circumboreal forest with scores falling under 10 when approaching the Arctic Circle, and many mountain ranges such as the Alps or the Carpathian mountains. Patagonia and northernmost tundra steppes of North America and Siberia show a score lower than one. The coast of the Gulf of Alaska, the Plateau of Tibet, and a large part of Central Asia also show similarly low levels of risk.

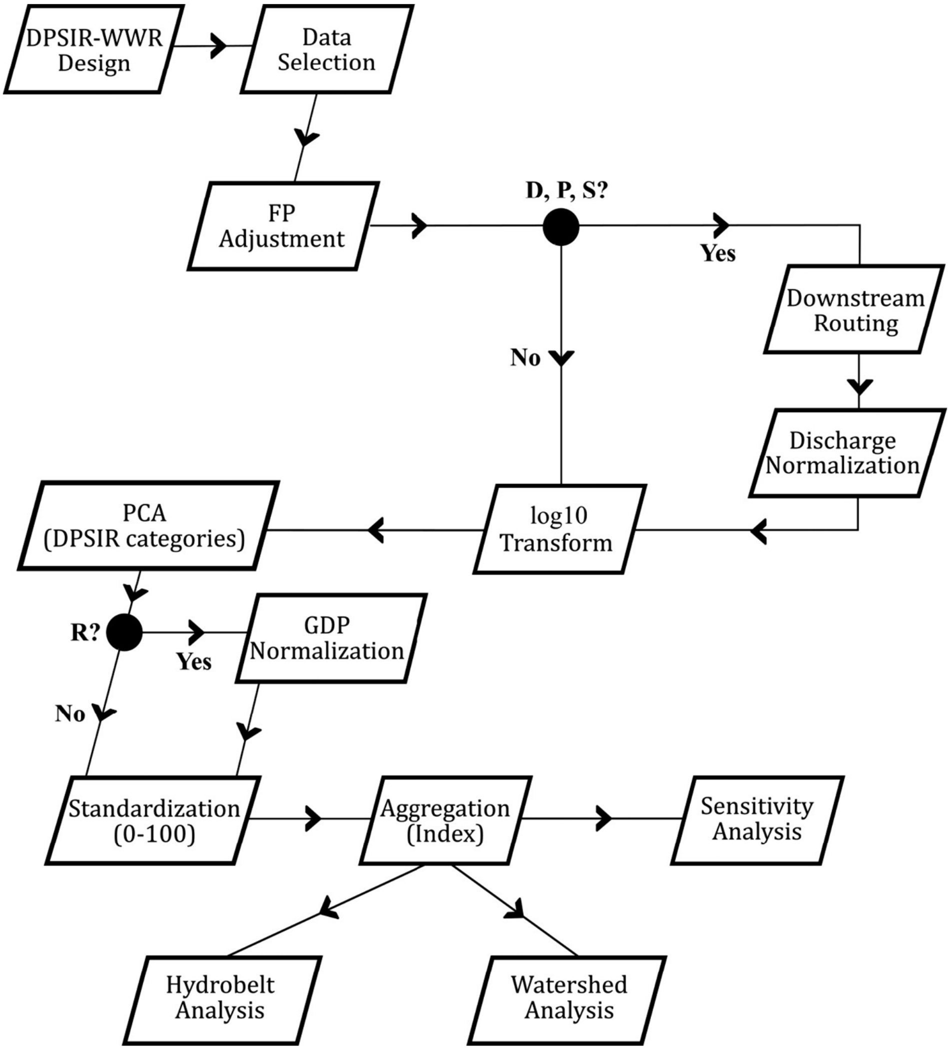

Fig. 2. Geoprocessing steps for the creation of the global WWR index. 'FP' stands for fire occurrence probability, 'log10' for logarithm base-10, and 'PCA' for principal component analysis. If indicators were part of the Driving Forces, Pressure, or State categories they were processed through the downstream routing and river discharge normalization steps.

A closer look at the WWR index scores by hydrologic belt (Fig. 4) reveals the factors controlling the wildfire risk to water supply in the different regions of the world. The boreal (BOR) belt shows an important variability in the final score values, although scores remain <20. The individual contribution of DPSIR global indicators is larger for Impacts and Pressure. The North and South mid-latitude (NML and SML) and the South subtropical (SST) belts show a similar pattern in the contribution of global indicators, with an overarching dominance of the Impact category (average scores are ~12.5, ~10, and ~12 respectively), followed by the State category (average score is ~5 in all three regions). The Response category remains well represented for NML and SML (average score is ~2.5) but is lower than 2.5 for SST. However, NML shows a larger variability in final scores whereas SML and SST show lower final scores in general. The North dry (NDR), North subtropical (NST), and Equatorial (EQT) belts are all characterized by a quasi-absence of Response values and a dominance of the Impact category, especially for NST and EQT (average score are ~12.5 and ~10 respectively). However, the distribution of index scores is highly variable between these three belts, with NDR showing in general higher scores. The Southern dry (SDR) shows an intermediate pattern, with low but existing Response contribution associated with a lower Impact category and final risk values clustered around 20.

The fine-scale analysis of 16 watersheds (Fig. 5) in regions known for their fire activity confirms the pattern shown at the hydrobelt level, underlining the importance of the impact and resilience categories in the control of final risk scores. Haifa, Marseille, Melbourne, and San Francisco, despite high levels of impacts, see their final score diminished because of their response capacity, whereas Guadalajara, Istanbul, Pune, Palangkaraya, and Quito do not show this response capacity for similar levels of impact. The cases of Denver, Fort McMurray, and Yakutsk show a different pattern where the drivers, pressure, and state categories account for a greater role in the final score, although the low response capacity coupled with higher Pressure levels in Yakutsk probably explains the final highest score (46.2).

4. Discussion

The creation of a spatial index showing the geography of wildfire-water risks to water security was motivated by three objectives: to create a robust framework, to study the WWR's geography, and to raise awareness about the WWR. We believe that the DPSIR framework for the analysis of the WWR is robust, in line with other studies presenting the DPSIR as a useful tool for the development of environmental indicators, from a global to a regional scale (Freudenberger et al., 2010). It also provides informative insights at the scale of large urban areas, although further location-specific data (i.e., finer spatial resolution) would make the approach better adapted to management purposes (Jago-on et al., 2009; Kelble et al., 2013). The global geography of the WWR displays similar risk levels among many regions of the world, important information that suggests there are opportunities to transfer skills and

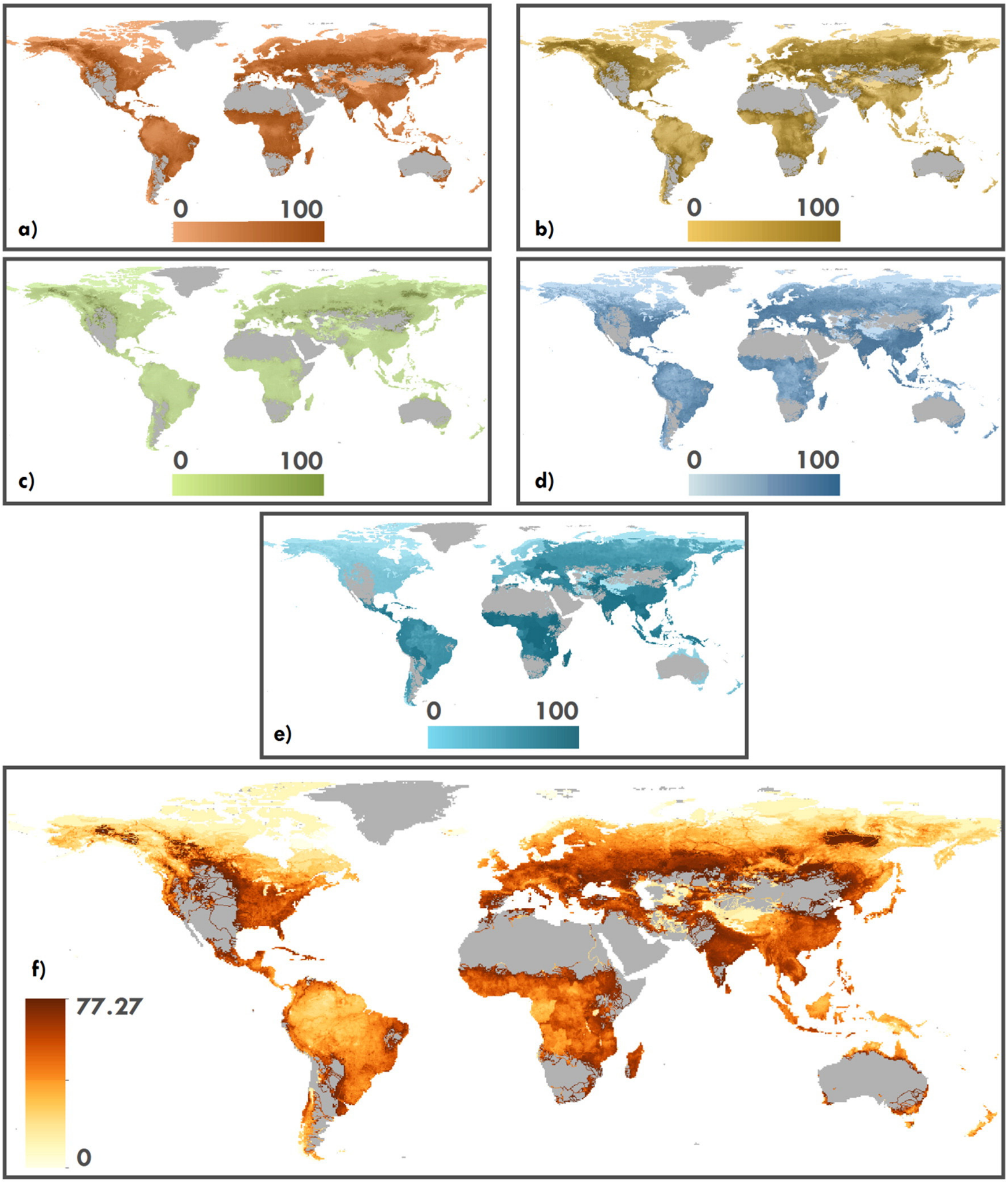

Fig. 3. Maps of the standardized global indicators, with: a) drivers, b) pressure, c) state, d) impact, e) response; and f) the final WWR index (unitless) resulting from the weighted sum of the global indicators. The color palette used for maps a) through e) is the same as Fig. 1. The color scheme applied to the final index follows an equalization stretch of the histogram to enhance the contrast between scores. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

technologies from WWR-prepared countries, like USA or Australia, to unprepared countries. However, such transfers would require adaptation to regional and local socio-ecological settings. Indeed, according to our results, the top-down controls of the risk result in important geographic discrepancies driven by three major aspects: the size of the exposed population and the magnitude of other values at risk, the capacity of exposed human and natural communities to face the risk and respond to a disaster situation, and the gravity of post-fire hazards. In this respect, the index shows commonalities with other studies related to water security and wildfire risk, in which regionally strong population growth and deficient economies drive the exposure and the vulnerability to the risk (Chuvieco et al., 2014; Gain et al., 2016; Veldkamp et al., 2016). The potential impacts on freshwater ecosystems could also endanger critical food sources for >150 million people around the world, a majority of them living in developing countries (McIntyre et al., 2016). Nonetheless, our results also show that developed regions, such as North America and Europe, are not immune to the hydrogeomorphic consequences of wildfires, as shown by Emelko et al. (2015) in Canada and White et al. (2006) in Australia. Those consequences may exacerbate existing water challenges linked to the increasing water demand or the ongoing degradation of freshwater resource quality (Green et al., 2015; McDonald et al., 2014; Schewe et al., 2014). Our work underlines the connections between fire, water, and soils at a global scale, adding to the threats to rivers systems listed by Vörösmarty et al. (2010) and Ceola et al. (2015). Combined with other decision-support tools, the application of our framework adapted to

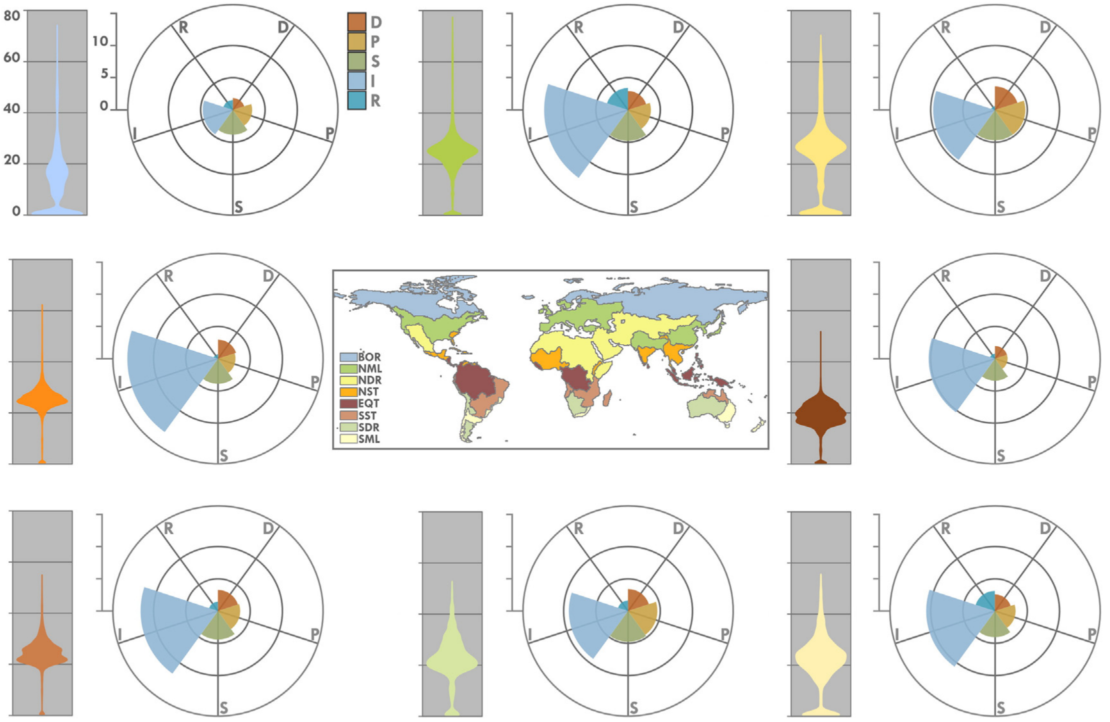

Fig. 4. Distribution of global WWR index scores per hydrobelt (violin plots) and the respective contribution of DPSIR categories to the standardized global WWR index (polar plots) aggregated per hydrobelt. The color palette used for each category is the same as Fig. 1. For readability purpose, the Response category presented here has been GDP-adjusted (multiplied), so higher values show higher response capacities, whereas the final index score uses GDP-normalized values (see Data and methods). The hydrobelts are: BOR = Boreal; NML = North Mid-Latitude; NDR = North Dry; NST = North Subtropical; EQT = Equatorial; SST = South Subtropical; SDR = South Dry; SML = South Mid-Latitude. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the WWR can feed further thinking on the integration of wildfire risks into water security governance (Bell, 2012; Tscherning et al., 2012).

More than a half of human population now lives in urban areas, following a global urbanisation trend that is expected to continue (Seto et al., 2011). Meanwhile, there is an increasing concern as to the vulnerability of ever-growing cities to natural hazards and water supply disruption (Hoekstra and Mekonnen, 2012; Jackson, 2006). Several recent initiatives, such as Global Forest Watch-Water from the World Resource Institute (Qin et al., 2016), Urban Water Blueprint from the Nature Conservancy (McDonald and Shemie, 2014), and 100 Resilient Cities (http://www.100resilientcities.org) have identified cities whose watersheds are exposed to wildfires. Our results confirm the risk posed by wildfires in several water basins supplying surface water resources to large urban areas, which emphasize the importance of considering the WWR in enhancing city resilience (Kinoshita et al., 2016; Martin, 2016). The historical fire season experienced by Chile in early 2017 provides further demonstration of existing interconnections between wildfire activity and water security. As the fire was spreading through a scorched countryside, it damaged numerous water distribution facilities, consequently limiting the water supply to firefighters already challenged by water shortages due to non-reliable water distribution systems (International Federation of Red Cross and Red Crescent Societies, 2017). Subsequent rainstorms in the widely burned Maipo River watershed, supplying Santiago, caused landslides and floods that further disrupted water supply to 5 million people.

The protection of watershed's natural capital has been overwhelmingly supported to assure the long-term provision of freshwater ecosystem services in urban areas (Andersson et al., 2014; Muning et al., 2011). Emelko et al. (2011) emphasize the need for source water protection from severe wildfire events, a statement enforced by the recent report ‘Beyond the source’ by the Nature Conservancy (The Nature Conservancy, 2017) which places wildfires as a critical threat to freshwater services. Although recent studies point at an ongoing decrease in global annual area burned (Andela et al., 2017; Doerr and Santín, 2016), the expansion of anthropogenic activities in natural areas leads to a multiplication of wildland-society interfaces (Le Page et al., 2010), potentially favoring disastrous consequences of wildfire activity on water supply reliability, especially in developing countries (Aldersley et al., 2011). Burke et al. (2013) also point to the post-fire water pollution from interface fires in urbanised areas where anthropogenic pollutants, such as heavy metals, can substantially leach. We argue that our results may help in supporting an enhanced protection or restoration of ecosystem services in watersheds supplying critical freshwater resources.

Our study raises questions about the future of wildfire-water risks to water security in a context of global environmental change. A growing number of studies document the vulnerability of coupled human-and-natural systems to these changes (Rockström et al., 2009) and the future associated challenges of water security they will have to overcome (Bogardi et al., 2012). The predicted alteration of climate, land use, and human demographics will affect fire activity (Flannigan et al., 2009), natural habitat health (Seto et al., 2012), soil properties (Hicks Pries et al., 2017), and water availability (Van Vliet et al., 2013). These ongoing modifications (Dodds et al., 2013; Jolly et al., 2015) will certainly change the nature of the WWR (Bladon et al., 2014). Developing countries, which are already the most vulnerable according to our results, will probably experience even more constant and pervasive effects of climate change (Harrington et al., 2016). In this respect, the WWR should be seen as an emerging risk, whose identification is one of the priorities of the 2015–2030 Sendai Framework for Global Disaster Risk Reduction (UNISDR, 2015). Therefore, our results provide a baseline for scenario-based exploration of future global changes, and the DPSIR framework provides a ready-to-use tool for benchmarking the fate of the WWR to water security.

Although the weighting scheme is a common drawback of indexation work (Gain et al., 2016; Vörösmarty et al., 2010), we strived to keep ours as objective as the available information would allow based on the method proposed by Bitterman et al.

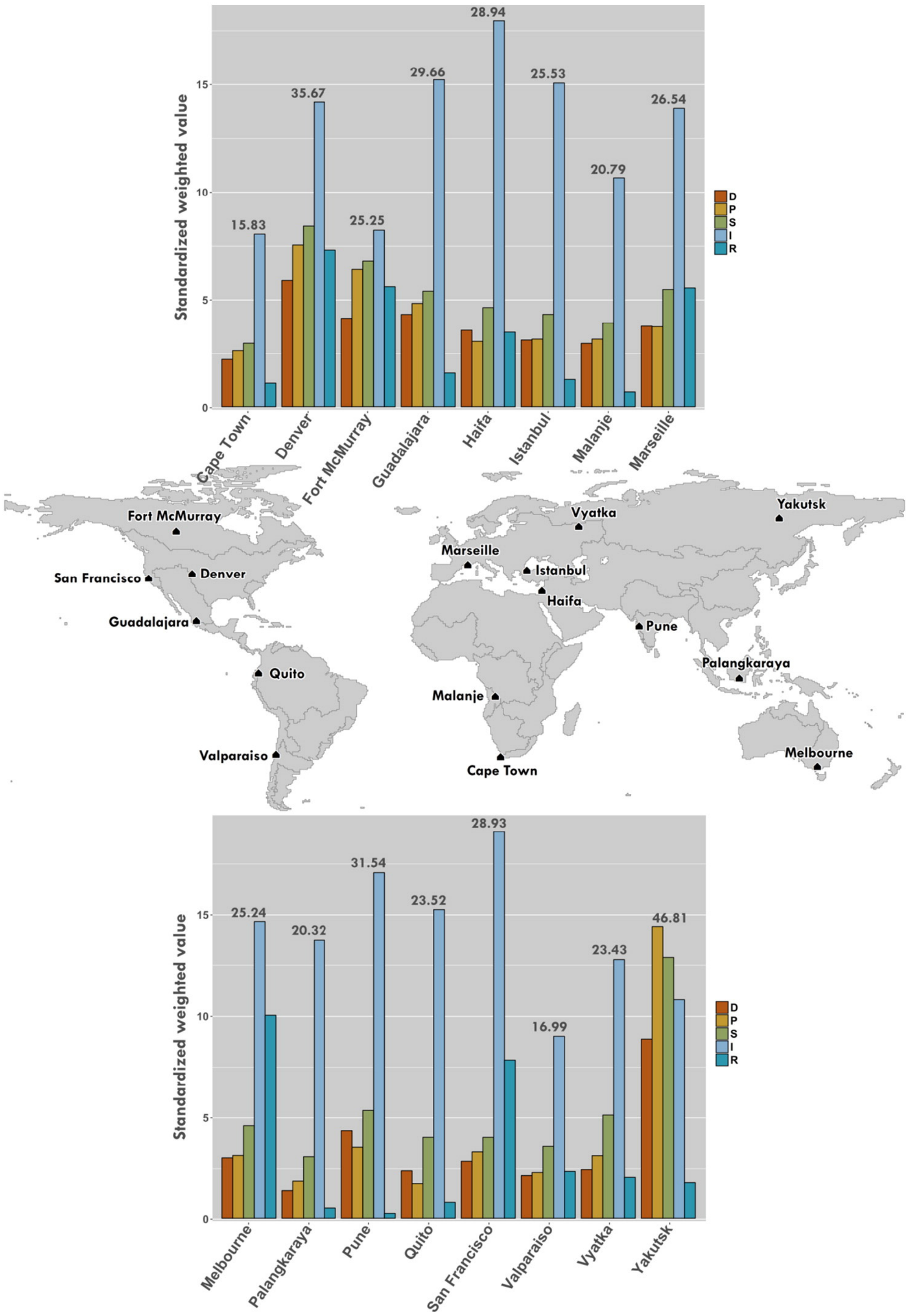

Fig. 5. Detail of global indicators' values for 16 selected watersheds across the world. The X-axis shows the mean value of each DPSIR global indicator for each watershed. The color palette used for each category is the same as Fig. 1. The number at the top of each graph shows the average risk score for the watershed. For readability purpose, the Response category presented here has been GDP-adjusted (i.e. multiplied), so higher values show higher response capacities, whereas the final index score uses GDP-normalized values (see Data and methods). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

(2016). Different weighting schemes would likely provide different results depending upon several indexation scenarios reflecting a diversity of governance priorities (Freudenberger et al., 2013). Further expert validation would also help to integrate other indicators and to combine them in a different fashion. For instance, in our case, indicators only appear once, but many post-fire hydrogeomorphic phenomena and their consequences can overlap several DPSIR categories and thus could be integrated several times. Regardless the final aggregation choices (e.g., weighting or number of indicators), even the presumed best index will suffer from robustness issues that must be spatially identified (See Appendix C) (Freudenberger et al., 2012; Robinne et al., 2016). Moreover, any global approach depends on the use of proxies, and therefore is subject to interpretation as to the relevance of any indicator (Vörösmarty et al., 2010). We chose to represent the main post-fire dynamics and water security constraints as presented in the literature, but this information can vary widely among different coupled human-and-natural systems. This point, therefore, must be kept in mind when interpreting the results presented here. Furthermore, this kind of information is lacking in many parts of the world, pointing at the accessibility to adequate data as another classic limitation of such work (De Bono and Mora, 2014).

Despite an increasing availability of data at a global scale, many datasets relevant to this study, such as the water stress index or environmental flows, were produced one to two decades ago; we suggest they should be revised on a continuous manner so their relevance to assess and monitor global environmental issues is maximal. Many data related to population welfare were available only in an aggregated fashion (i.e. country-scale) and could not be used directly in spatially explicit approaches. Other variables, such as smoke deposition or extreme precipitation, were available at a coarse resolution that needed downscaling, thereby introducing a certain level of error due to resampling. Finally, data such as firefighting expenditures, technological water-treatment capacities, or human and economic losses specifically related to the WWR are simply nonexistent at a global scale. It is interesting to note that in the "big data" world, we still lack spatially explicit (i.e. pixel-based) global datasets that are regularly updated, at a single standard resolution, especially those representing social indicators, and that many parts of the world suffer from a deficit in scientific information (Leidig et al., 2016). The science of post-fire hydrogeomorphology is well developed, and the availability of databases on post-fire debris (Parise and Cannon, 2003) or general post-fire hydrological effects (Hallema et al., 2017) are encouraging efforts, although no mention of downstream consequences on the water supply are reported. There is, therefore, a need for a global database that maps key WWR indicators. In this regard, we argue that the creation of a global standardized protocol is critically needed to collect measurements pertaining to post-fire hydrological disasters, and results must be made available online, through the EM-DAT repository for instance, to advance global-scale WWR modelling.

5. Conclusion

The work presented here gives a global overview of the wildfire-water risk to water security. As any global index, its primary aim resides in giving an overall perspective of an issue that could affect most parts of the globe. In line with the Sendai Framework for Disaster Risk Reduction, we used the DPSIR analysis framework to provide new insights and raise awareness about this emerging risk. Although actual risk management actions take place at finer scales, a global view of this growing concern offers a new facet to consider in the governance of water-related risks. Our spatial index may help further investigate hydrological systems where the water supply is already under pressure because of urban development, ecosystem degradation, or climate change. As indices are geared toward environmental performance improvement, our framework introduces a tool for long-term monitoring of actions toward the reduction of post-fire threats to water security. Our work could also help to reconsider the place of fire in the landscape and to foster the use of "good fires" as a means to preserve water-related ecosystem services. We believe that our results represent an important contribution to the current knowledge of the global geography of risk, as well as provide new insights for the achievement of global water security.

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.scitotenv.2017.08.112.

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