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The River Wild: towards a global assessment of wilderness rivers

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1. Introduction

Wild rivers are important, not only for aesthetics and recreation, but also for delivery of ecosystem services such as clean water, irrigation and maintenance of nutrient cycles. This paper looks at the global distribution of wild rivers using GIS-based approaches with the aim of developing and exploring more unified approaches to wild river identification and appraisal. There are several published versions of a global wilderness map but no integrated global map of the distribution of wild rivers. Global hydrological datasets are integrated here with global wilderness maps to identify the top 10% wildest rivers at both global and continental scales. Thoughts are given in the discussion and conclusions on the dangers of over-reliance on global datasets and the need for multi-scale analyses incorporating finer scale datasets and local knowledge. An example local scale analysis is presented for the Salmon River, Idaho.

2. Why rivers?

Rivers are an integral part of all landscapes. Running water can be found almost anywhere on the planet from the Polar regions to the driest of deserts. Rivers perform a vital role in connecting mountains to the sea, and are conveyors not just of water, but also sediments and dissolved solids and nutrients. They are agents of change, reflecting cycles of flood and drought, and periods of erosion after which sediments are transported downstream and ultimately deposited in the oceans. Rivers provide habitats for wildlife, not just for fish and other aquatic organisms, but for all biodiversity that relies on them to provide water that is essential for life. For us as humans, rivers provide us with water to drink, to irrigate our crops and power our industry. They also provide us with stimulating recreational environments and some of the finest scenery on the planet. Yet over the years we have over-exploited many of our rivers. We have used them as a water source, for travel and transport, and as convenient dumping grounds for our waste. We have sought to control rivers with dams and levees, attempting to tame their flood-drought cycles and put them to work generating electrical energy. As a result, many rivers are now pale reflections of their former selves and without protection many more rivers may well be degraded and lose their wildness and the ecosystem services that they provide. Being able to recognise and identify the world's remaining wild rivers in a rigorous and repeatable manner is perhaps the first step towards better protection.

3. Protection for wild and scenic rivers

Our appreciation of the natural beauty of rivers and recognition of the threats they face provides the backdrop against which the Wild and Scenic Rivers Act (1968) was written. The National Wild and Scenic Rivers System (NWSRS) was created by the United States Congress in 1968 (Public Law 90-542; 16 U.S.C. 1271 et seq.) to preserve those rivers with outstanding natural, cultural, and recreational values in a free-flowing condition for the enjoyment of present and future generations.

The Act is intended as a safeguard for the wild character of selected rivers, while recognizing the potential for their appropriate (i.e. recreational) use and development.

The Act classifies rivers as *wild*, *scenic*, or *recreational*. These are summarised in Table 1.

Class/Type	Description
Wild River Areas	"Vestiges of primitive America" Those rivers or sections of rivers that are free of impoundments and generally inaccessible except by trail, with watersheds or shorelines essentially primitive and waters unpolluted. These represent vestiges of primitive America.
Scenic River Areas	"Accessible by road but largely undeveloped" Those rivers or sections of rivers that are free of impoundments, with shorelines or watersheds still largely primitive and shorelines largely undeveloped, but accessible in places by roads.
Recreational River Areas	"Readily accessible and somewhat developed" Those rivers or sections of rivers that are readily accessible by road or railroad, that may have some development along their shorelines, and that may have undergone some impoundment or diversion in the past.

Table 1. River class/type in the National Wild and Scenic Rivers Act (1968) (After http://www.rivers.gov)

As a piece of legislation, the Act is primarily applied to both Federal and Private lands and does not affect existing water rights. The Act essentially prohibits Federal support for dam construction or other in-stream activities that could prove detrimental to some of the country's free-flowing rivers including impacts to flows, water quality or the recreational resource. The NWSRS currently protects over twelve thousand miles of over two hundred rivers in forty states. While this may sound like a substantial number it is in fact less than one quarter of one percent of the United States' rivers.

The United States is not alone in providing a level of protection for its free-flowing wild rivers. Similar systems are present in Canada, Australia and New Zealand. The Canadian Heritage Rivers System (CHRS) is similar that of the NWSRS of the United States. This was established in 1984 and "gives national recognition to Canada's outstanding rivers and encourages their long-term management to conserve their natural, cultural and recreational values for the benefit and enjoyment of Canadians, now and in the future" (http://chrs.ca/). There are currently 42 such rivers designated under the CHRS, totalling some 12,000km of river across the whole of Canada. However, unlike the United States NWSRS, the CHRS is a voluntary process involving the nomination of rivers by provincial/territorial governments after which rivers are only designated after a rigorous screening process. The CHRS recognises the continuing and historical importance of rivers to indigenous people as well as early settlers and to contemporary industry, landscape and environment.

New Zealand also has similar legislation and protects wild waters for scenic, recreational and habitat purposes. This is implemented through Water Conservation Orders (WCOs) and came into force in 1984 with 15 rivers throughout New Zealand being protected under this legislation (NZCA, 2011). WCOs can be applied to all water bodies including rivers, lakes, ponds, wetlands and geothermal waters. They are used to provide protection to the water body's natural state as habitats for terrestrial and aquatic life, for its "wild, scenic or other natural characteristics", its scientific or ecological values and recreational, historic, spiritual and cultural purposes. The Whanganui River was recently granted "human rights" in recognition of the river as a Māori ancestor, thus setting an interesting precedent for preventing misuse of a river.

In Australia, the Wild Rivers Project sets out to "identify rivers, encourage protection, engage in voluntary management of the whole catchment, and promote the values of wild rivers" (http://www.australia.gov.au/about-australia/australian-story/australias-wild-rivers). While the rivers represented in the United States NWSRS are included based on a case-by-case evaluation against the criteria listed in Table 1, the Australian system adopts a more quantitative, GIS-based approach. This builds on the Australian National Wilderness Inventory (NWI) which is itself a GIS based mapping of wilderness quality across the whole of Australia (Lesslie and Maslen, 1995). The Australian approach to designating their wild rivers is based on a River Disturbance Index (RDI). This is modelled across all rivers using a combination of spatial indices describing wildness within the river's catchment. These include land use, settlement, infrastructure and extractive industry and point pollution sources, together with indices describing specific impacts along the river itself including dams/impoundments, flow diversions/water abstractions and levees. Mapped at a national scale, the RDI describes a continuum of river disturbance from near pristine to highly degraded (Stein et al., 2002; Stein et al., 2001; Stein et al., 1999).

In Europe, the Water Framework Directive provides a framework for protecting water quality and habitats throughout the European Union with the emphasis on integrated catchment management. While there may be few if any truly wild and free-flowing rivers of any appreciable size left in Europe there is a growing recognition of the value of wild rivers for associated values of natural habitats and processes, recreation and heritage. The European Rivers Network (ERN) is an NGO set up to promote this ideal and develop relevant projects throughout the EU working on the back of protected area legislation such as Natura2000 and the Habitats Directive (http://www.ern.org/en/).

4. Integrated thinking

If we look solely at the river and its floodplain when thinking about protecting the world's remaining wild rivers then we are in danger of missing a key part of the picture. Rivers are not just convergent linear networks but are connected to the entire landscape via all the processes inherent within the hydrological cycle (infiltration, overland flow, through flow, percolation, etc.) that govern runoff generation. As a result, current thinking in water and land management focuses more on integrated catchment management since to protect the river and its values associated with flow regimes, water quality, recreation and wildlife, we must also act to protect its catchment (Mitchell and Hollick, 1993). It has long been recognised that clean water supplies come from catchments that are protected from degradation be that through agriculture, deforestation, industry, extractive land uses or settlement. For this reason, metropolitan areas often seek to protect the watersheds providing the city's water supplies rather than pay for expensive "end of pipe" treatment of polluted water. A good example is New York City Water Board's purchase of key watersheds in the Catskill Mountains (Weidner, 1974).

It follows therefore that protecting the wilderness qualities of the river catchment is the key to protecting the wildness of the river. If we can map that connectivity between land and river and how human activity within the catchment (including settlement and transportation infrastructure) and modification via human land use (agriculture, forestry, etc.) influences the hydrological functioning of watersheds such as providing natural water flows, then we can create a draft inventory of wild rivers using purely global datasets. The remainder of this paper will explore the potential and difficulties of such a model and approach.

5. Methods

The work presented here uses global datasets to identify the wildest rivers in the world. The datasets used here are the Human Footprint version 2, Hydro1K 30ArcSecond global DEM, and the Global Reservoir and Dams database (GRanD). Using a nested multi-scaled approach, it is possible to sequentially identify the wildest rivers at a global level, in each continent and then in each country, though for many smaller countries (e.g. Belgium or Belize) the limited resolution of the global datasets could easily present a problem requiring substitution of national level datasets. The basic model proposed links wilderness quality within a catchment to its river using a weighted flow accumulation model to create a classification of rivers and their catchments similar to that described by the Australian Wild Rivers Project, from pristine to heavily modified. This works by totalling the level of upstream human impact based on the assumption that catchments with greater upstream impacts will exhibit corresponding impacts on the wildness of the river including modifications to natural flow regimes, sediment loads and pollution.

Global wilderness maps range from the McCloskey and Spalding map published for the 4th World Wilderness Congress in 1987 (McCloskey and Spalding, 1989) to the Human Foot print version 2 "Last of the Wild" project in 2005 (Sanderson et al., 2002; WCS, 2005). Various other global scale maps and databases exist showing roadless areas (Ibisch et al., 2016), human impact on the world's oceans (Halpern et al., 2008) and declining wilderness areas (Watson et al., 2016). Except for the McCloskey and Spalding map, which was produced largely by hand from Jet Navigation Charts, all the above works are made possible by the availability of global digital spatial datasets. The Human Footprint data developed by CIESIN and WCS can be used as a global wilderness quality index to provide information on how settlement, transport infrastructure and land use negatively impact on natural ecosystems (Sanderson et al., 2002).

Hydro1K is a hydrological corrected digital elevation model which includes a river network, a flow direction matrix and six levels of nested catchments using Pfafstetter units (Verdin and Verdin, 1999). Pfafstetter units are a means of codifying nested drainage basins based on a hierarchical system from continental scale drainages (level 1) through to higher orders (levels 2-6). Within the system there are three types of drainage: basin (a drainage area that does not receive water from any other drainage), inter-basins (which receive water from upstream basins) and internal basins (which do not contribute water to another drainage or ocean/lake). The coding allocated to each basin is unique and allows the user to identify where a drainage sits within the nested series of basins below level 1. Not all the world’s catchments are codified to the same degree. There are some large and poorly delimited areas within the Amazon basin, Himalayas, Eastern and Southern Europe, Southern Africa and the Arabian Peninsula. The GRanD database (Lehner et al., 2011) is used to identify unregulated rivers and augment the Human Footprint dataset.

The Hydro1K flow direction matrix and Human Footprint version 2 data are used together to perform a global weighted flow accumulation analysis using the Hydrological Modelling tools in ArcGIS 10 to calculate how the level of human impact "accumulates" downstream through the drainage networks to show up the wildest rivers (i.e. those with highest upstream wilderness quality). Statistics on downstream human impact (minimum, maximum, mean, range, standard deviation) are then calculated for each of the six Pfafstetter levels in the Hydro1K nested catchments database which enables the classification of catchments on a scale of pristine to heavily modified.

6. Results

Basic classifications of the wildest rivers and their contributing catchment areas are presented in Figures 1-7. Figure 1 presents the global picture with the top 10% wildest river catchments highlighted, while Figures 2-7 show similar maps scaled for each of the continents (excluding Antarctica). Other catchments are classified into one of three groups based on percentiles along the wilderness index as follows: largely unmodified (90-60%), moderately modified (60-30%) and heavily modified (30% and below). Although it is possible to map every statistic for each of the six nested Pfafstetter levels we are principally interested here in the maximum wilderness quality within mid-level catchments that can robustly map the distribution of wild rivers without undue generalisation or too much detail. The maps presented are therefore for the maximum accumulated human impact within Pfafstetter level 3 catchments.

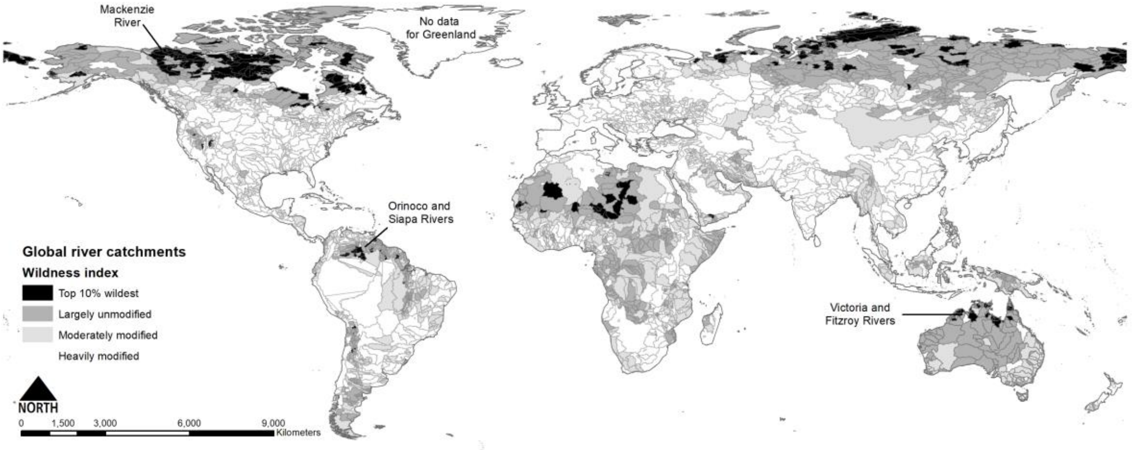

Figure 1. Global wild rivers

It can be seen from Figure 1 that many of the wildest rivers fall mainly into permafrost or desert environments. As such these rivers are likely to be ephemeral and only flow when fed either from seasonal ice/snowmelt (e.g. Mackenzie River in Canada) or high magnitude/low frequency flash floods events in desert areas. Mid-latitude rivers in temperate or moist tropical regions are not well represented in the top 10% of wildest rivers at a global scale with the exception being those within the intact tropical rainforest areas of northern Amazonia (e.g. Orinoco and Siapa) and the larger rivers draining northern Australia (e.g. Victoria and Fitzroy).

The distribution of wild rivers at a continental scale shows a similar pattern (see Figures 2-6) though more mid-latitude rivers exhibiting "normal" (i.e. constantly flowing with minimum base flow > zero) flow regimes are represented.

At a country level the patterns are more widely dispersed. Figure 8 shows the pattern of wild rivers and their catchments for the Lower 48 US states. While most of the top 10% of wildest catchments are in the west and many are internal basins in the deserts of Nevada, California and Arizona, several key mountain river catchments are present including many within the NWSRS such as the Clearwater and Salmon Rivers.

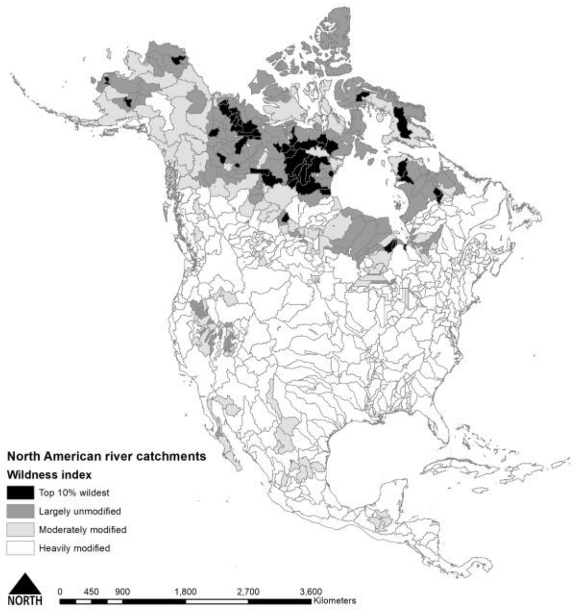

Figure 2. North and Central America

Figure 3. South America

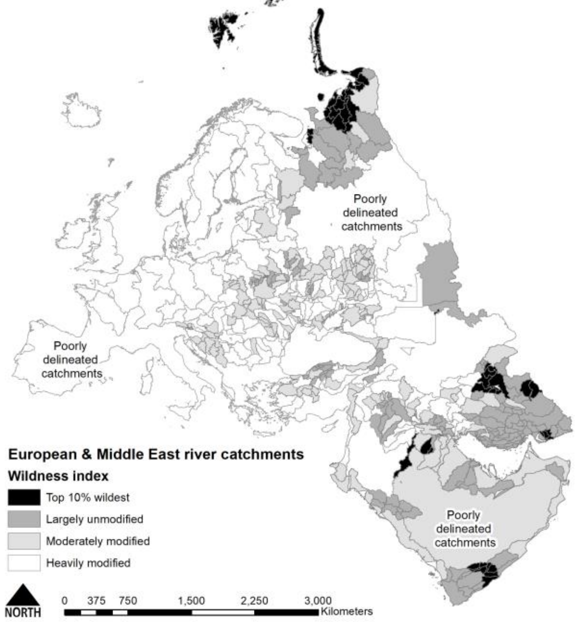

Figure 4. Europe and the Middle East

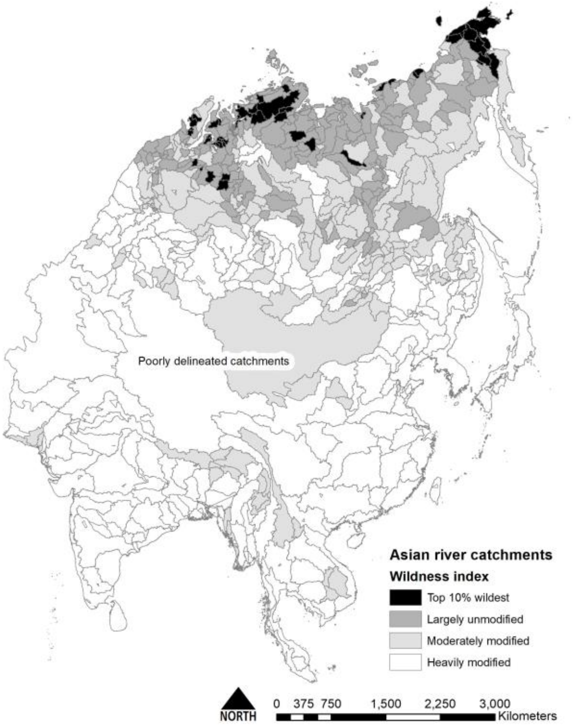

Figure 5. Asia

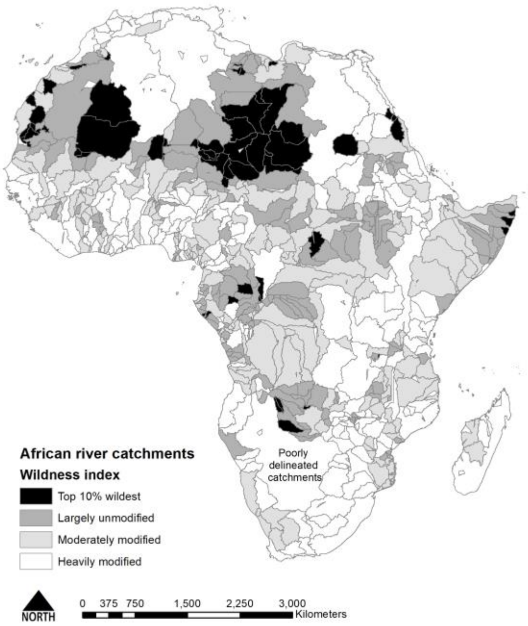

Figure 6. Africa

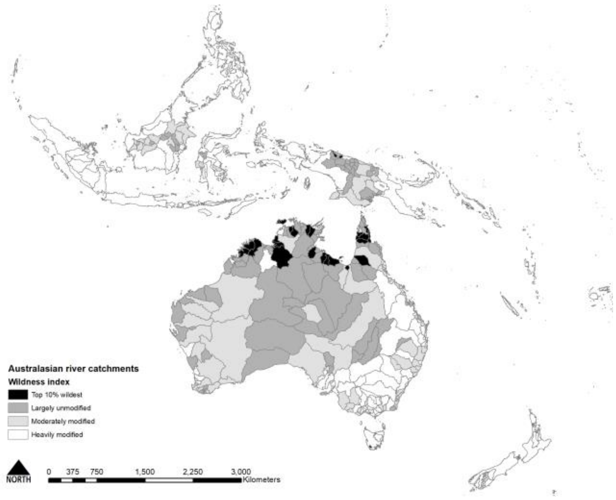

Figure 7. Australasia

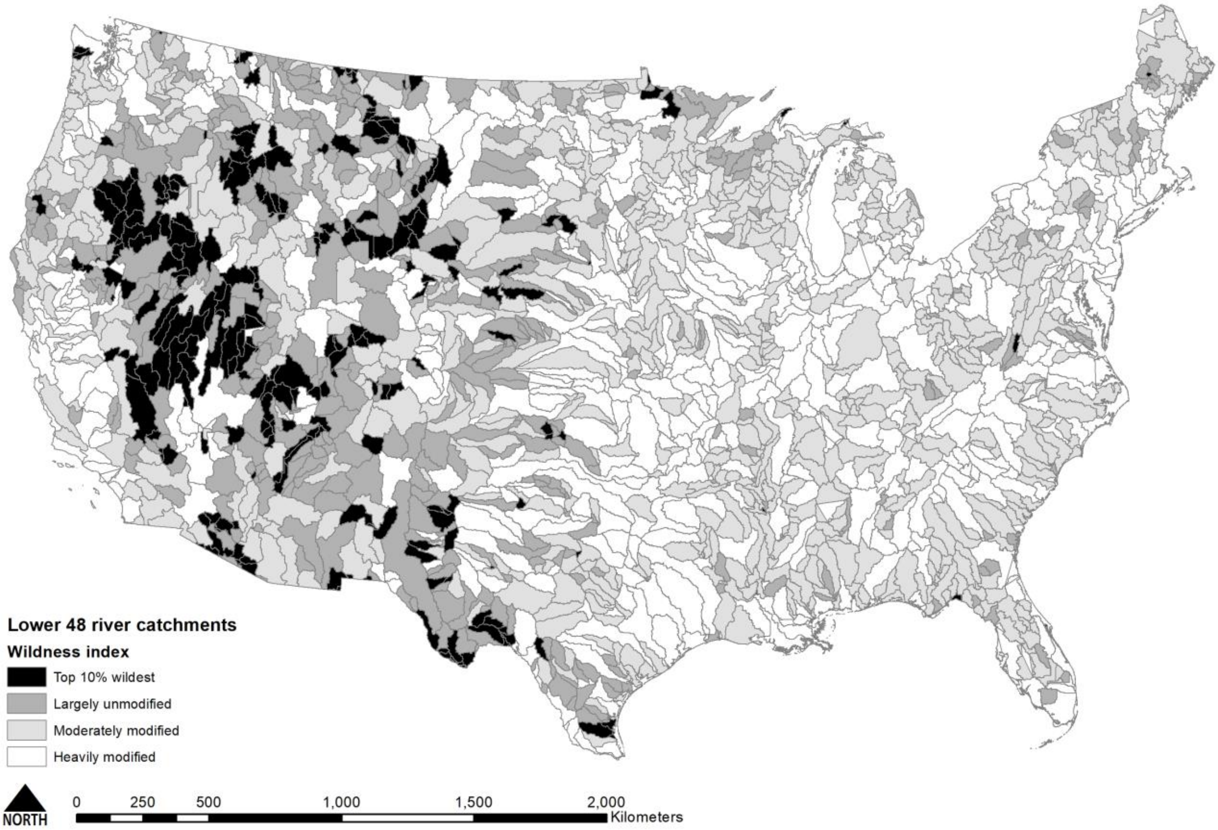

Figure 8. USA Lower 48 States

7. Discussion

Global datasets are generally inconsistent, coarse scale and reliant on highly generalised data sources. This creates problems for consistent mapping at a high quality such that it is often better to map at a country scale using national datasets that, while varying in quality between countries and across national borders, will at least be internally consistent (Carver and Fritz, 2016). The inconsistency and uncertainty inherent in global datasets makes continental and country-to-country comparisons difficult and open to criticism.

As the number of papers published using global datasets increases, it is important to both recognise and question the validity of the results presented. Recent examples include global analyses that purport to show catastrophic declines in wilderness areas since the early 1990s (Watson et al., 2016). While the general global trends reported are likely to be true, the quality of the data and therefore the subsequent analyses are questionable when examined in detail at the national scale and especially where reductions in human impacts are reported (http://wcshumanfootprint.org/). This is largely due to changes in the way the datasets are compiled and recorded between 1993 and 2009 and variations in the detail at which data on topics such as land use and population are recorded between countries.

The same can be said of the draft analyses presented here as this uses some of the same datasets (i.e. the Human Footprint version 2 database) to define spatial patterns in the variability of human impact, though here we are not trying to model change over time. The Human Footprint version 2 data relies heavily on global datasets including human population pressure (population density), human land use and infrastructure (built-up areas, night-time lights, land use/land cover), and human access (coastlines, roads, railroads, navigable rivers), all of which are subject to generalisation leading to errors of both omission and commission. The resolution of 1 kilometre grid leads to further generalisation. The reliability of key datasets varies spatially between countries particularly when relying on national census data for information on population density.

The Hydro1k global used here aims to provide comprehensive and consistent global coverage of topographically derived data sets, but is based on the GTOPO30 global terrain model which at 30 arc -second equates to roughly 1 kilometre grid on the ground. While it is theoretically possible to use a terrain model of this resolution, the coarse resolution inevitably leads to errors in defining flow paths and watersheds especially in low relief areas where low variability between adjacent cells in the terrain data make determining the correct flow paths difficult and prone to error. The HydroSHEDS database is a more detailed and refined model, being based on the SRTM 90m data and providing nested Pfafstetter codes down to level 12 though accuracy is limited above 60° North and below 60° South is limited due to lack of SRTM data and replacement with the Hydro1K model.

Other datasets used here include the Global Reservoir and Dams database (GRanD). This is used to modify the Human Footprint data such that the impact of dams and reservoir impoundments are correctly linked to downstream portions of the rivers affected. Again, as with any global dataset, there are errors of omission in this dataset. The dataset is limited to impoundments greater than 0.1km^3 (0.024 cubic miles) in size for which information is available (Lehner et al., 2011).

The modelling process for determining the downstream cumulative human impact within the Pfafstetter catchments from Hydro1K is based on the calculation of predicted flow directions and a weighted flow accumulation model within ESRI's ArcGIS package. The D8 algorithm used by ArcGIS assumes 100% runoff of all water entering the catchment and does not allow for losses to evapo-transpiration of groundwater percolation, though these could be modified accordingly.

Problems with the base data notwithstanding, by far the greatest cause for concern with the global analysis of wild rivers is the definition of the catchment boundaries themselves. These boundaries or watersheds can be defined for any point along the length of the river while the Hydro1k and datasets like it only provide a limited series of nested catchments. This is in effect an example of the well-known Modifiable Areal Unit Problem (MAUP) wherein the results of dividing the world up into a series of artificially defined reporting units can markedly influence the patterns seen in the mapped data (Openshaw, 1984). The catchments provided by Hydro1K are just one set of basins out of a theoretically infinite set of possibilities and while the local topography will determine the flow direction and the catchment watershed, the choice of pour-point above which to define the contributing area is critical in determining the shape and area of the catchment. As a result, the intersection with the human impact data and the catchment's position in the global hierarchy of wild rivers can vary widely depending on the catchment boundary used.

It is suggested that national or sub-national analyses utilising local scale data are almost certainly going to provide more reliable and robust outputs. Furthermore, a continuous analysis of the cumulative human impact and wildness quality for a series of finely nested catchments upstream of a closely spaced set of pour-points along the entire length of the river of interest could best be employed to define those sections of the river that best meet the three classes (or similar) described by the NWSRS. This is illustrated here for the Salmon River in Idaho which is part of the existing NWSRS and famous for its challenging white water rafting.

Figure 9 shows the Salmon River as a series of nested catchments. These are defined by over 3000 individual pour-points along the 700-kilometre (430 mile) river from its headwaters in the Sawtooth National Recreation Area to its confluence with the Snake River in the Hells Canyon National Recreation Area. These are defined and mapped using the 30m SRTM terrain data. Information on upstream catchment area, elevation, cumulative upstream human impact and its ratio to catchment area, distance of river from nearest road and level of human impact within 1km of the river are plotted against downstream distance to demonstrate the physical and wilderness characteristics of its long profile. These are shown in Figures 10-12 and demonstrate how the location of pour-points used to define catchments in databases like Hydro1k can effectively mask the true underlying patterns of physical and wildness indices when mapped and classified as in Figures 1-7. In this respect, it is likely that a mixed-methods approach to identification of wild rivers (e.g. one that combines elements of multi-scale mapping of a river's long profile with elements from the Australian Wild Rivers Project) together with validation using qualitative assessments (e.g. based on local knowledge and expert appraisal as with the NWSRS and CHRS) would produce the most robust results.

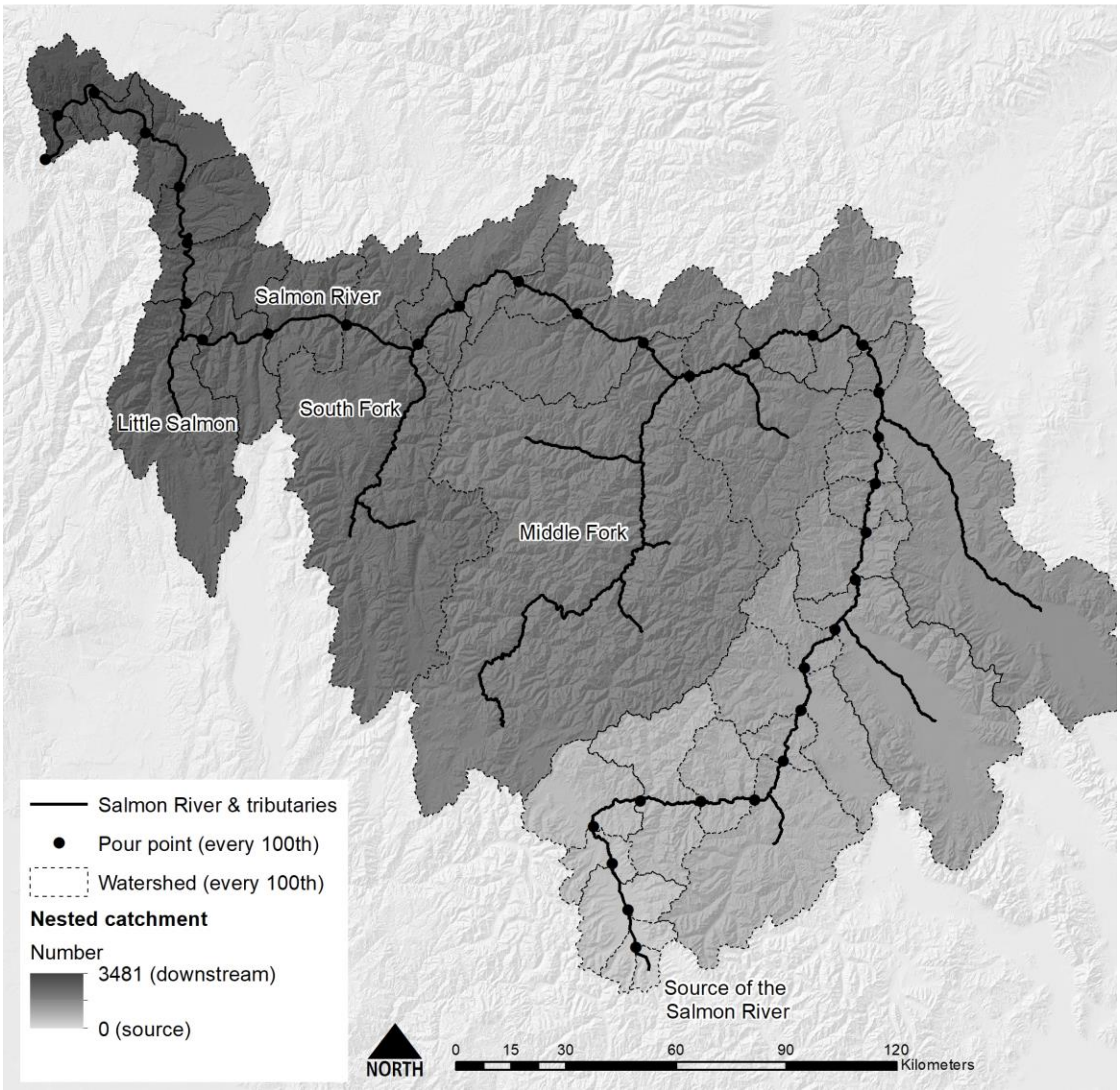

Figure 9. Nested catchments of The Salmon River

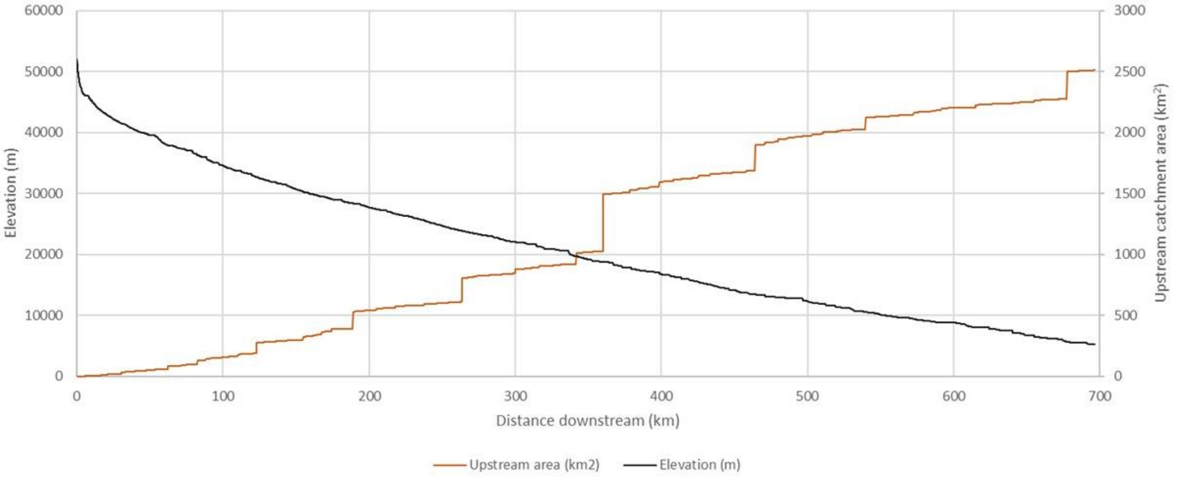

Figure 10. Salmon River long profile

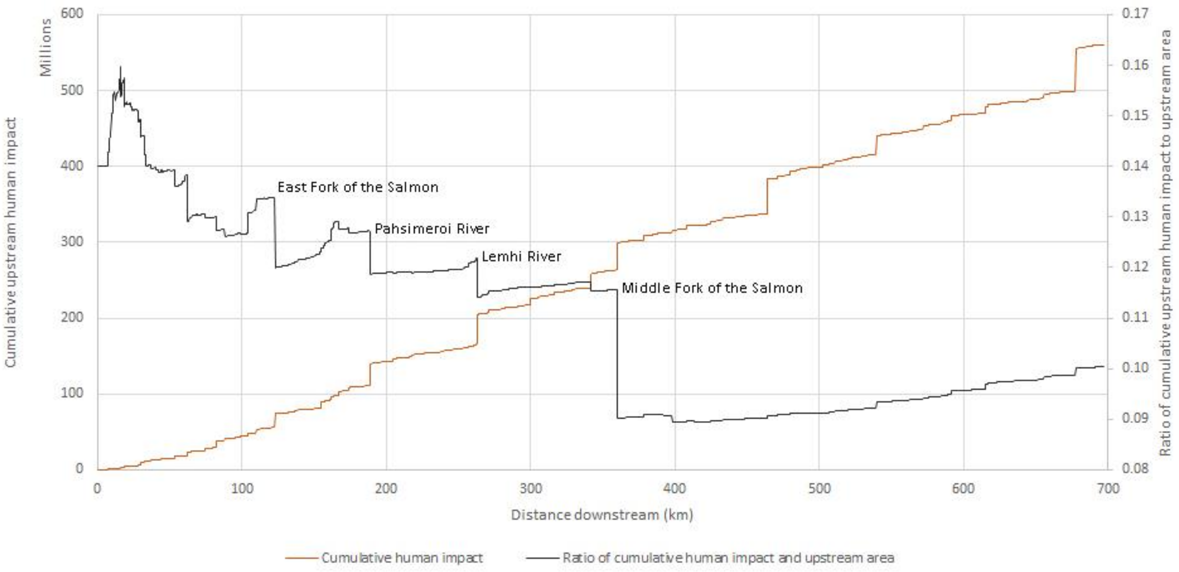

Figure 11. Salmon River cumulative downstream human impact

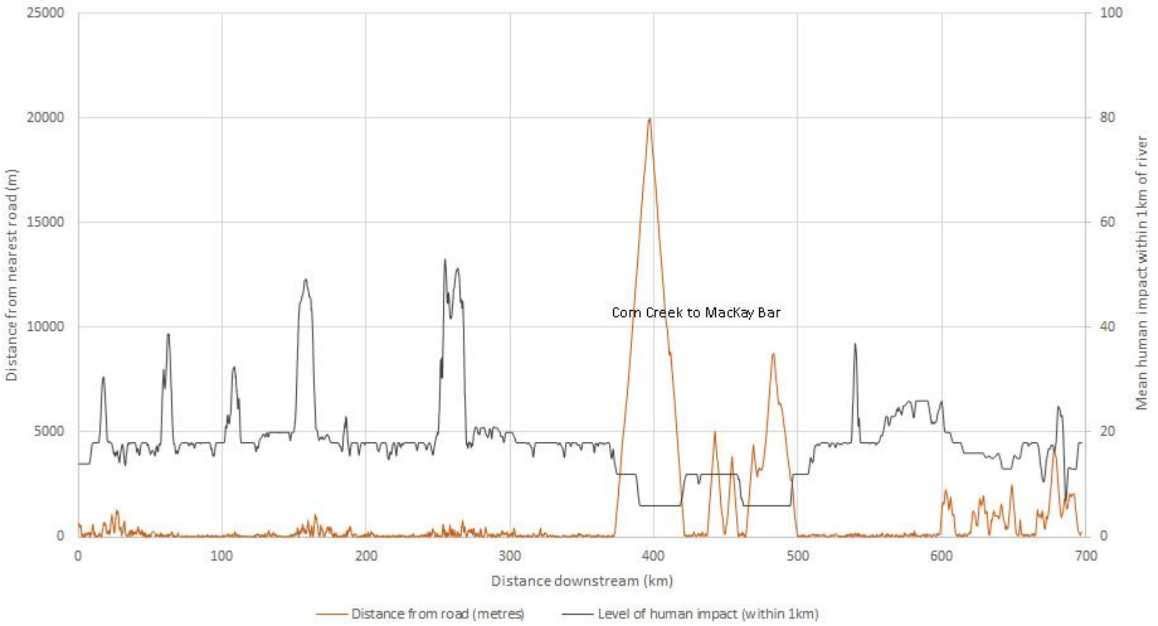

Figure 12. Salmon River wilderness indices

8. Conclusions

This paper looks at the potential for using global level datasets on hydrological networks and wilderness quality indices to develop a draft global assessment of wild rivers. While the combination of the Hydro1k and Human Footprint Version 2 datasets using a weighted flow accumulation model works well in technical terms, there are some serious concerns about the validity of the results when reported at global and continental scales within fixed catchment areas about accuracy and representation of real-world patterns. This is due to known limitations associated with global datasets, including coarse resolution, generalisation, variable accuracy and consistency across regions and national boundaries, as well as limitations in the use of fixed and arbitrarily defined catchment boundaries. As a result, it is suggested here that national and local assessments are required based on a combination of more detailed and reliable datasets together with a nested analysis of variations in wildness indices along the river's long profile. Used together with local knowledge and expert appraisals a more robust global assessment could be developed by building up national assessments across the globe. The practical logistics in validating results using local knowledge would be substantial but could be made manageable using crowd-sourcing techniques such as GeoWikis (Fritz et al., 2009) and participatory GIS models (Huck et al., 2014).

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Datasets used

Human Footprint v2 http://sedac.ciesin.columbia.edu/data/set/wildareas-v2-human-footprint-geographic

Hydro1k https://lta.cr.usgs.gov/HYDRO1K

GranD http://www.gwsp.org/products/grand-database/global-reservoir-and-dam-grand-database-project.html