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Increasing seasonal variation in the extent of rivers and lakes from 1984 to 2022

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Abstract

Knowledge of the spatial and temporal distribution of surface water is important for water resource management, flood risk assessment, monitoring ecosystem health, constraining estimates of biogeochemical cycles and understanding our climate. While global scale spatial-temporal change detection of surface water has significantly improved in recent years with planetary scale remote sensing and computing, it has remained challenging to distinguish the changing characteristics of rivers and lakes. Here we analyze the spatial extent of permanent and seasonal rivers and lakes globally over the past 38-years based on new data of river system extents and surface water trends. Results show that while the total permanent surface area of both rivers and lakes has remained relatively constant, the area with intermittent seasonal coverage has increased by 12% and 27% for rivers and lakes, respectively. The increase is statistically significant in over 84% of global water catchments based on Spearman rank correlations above 0.05 and p values less than 0.05. The results of our analysis are shared as the Surface Area of Rivers and Lakes (SARL) database, which contributes to improved understanding of the hydrological cycle and management of water resources.

1. Introduction

Climate change and population growth have placed considerable stress on our natural freshwater resources. Water demand has increased nearly 8-fold over the past century with an estimated 70% of the total used to meet irrigation needs (Siebert et al., 2010; Wada et al., 2016). To meet the increasing water demand, an estimated 16.7 million reservoirs have been built holding a predicted 8070 km^3 of freshwater (Lehner et al., 2016). Current water demand represents only 10% of our approximate annual renewable freshwater resources (Oki and Kanae, 2006). Nonetheless, water scarcity remains a significant problem around the world due to the variability of water in time and space (Oki and Kanae, 2006; Mekonnen et al., 2016). The hydrological cycle is also crucial to the health of our ecosystems and biodiversity that depend on the recurrence and seasonality of water to support life (Gleeson et al., 2020). Furthermore, inland waters are also an important component in biogeochemical cycles of CO$_2$ and methane that, by size, disproportionately contribute a significant portion to our total greenhouse emissions annually (Bastviken et al., 2004; Allen and Pavelsky, 2018; Matthews et al., 2020).

While the surface area of water is only one part of the hydrological cycle, it is the most accessible portion influencing human and ecosystem behavior and an important component in groundwater recharge (Oki and Kanae, 2006; Sibert et al., 2010; Gleeson et al., 2020). Knowledge of the type of waterbody, i.e. whether it is permanent, intermittent, or seasonall and whether it is part of a river system or a lake, is important to understand the role of water bodies in different hydrological processes, ecosystem support and biogeochemical cycles. The changing physical environment and its waterbody type due to droughts, floods or direct human alteration also alters migration patterns of humans, ecosystems, and their biodiversity (Neumann et al., 2015; Van Loon et al., 2016). In addition, the perennial and seasonal state of both rivers and lakes has important implications for ecosystem health (Messager et al., 2021) and carbon cycles (Keller et al., 2020). The type, extent and seasonality of waterbodies at a global basin scale is needed for improved water resource management sustained delivery of ecosystem services (Sheffield et al., 2018).

Planetary scale computing and analysis of remotely sensed imagery have led to a number of studies revealing the unprecedented impact of human resource management and climate change stress on the extent of water (Van Dijk et al., 2011; Wada et al., 2016; Pekel et al., 2016, Donchyts, et al., 2016). In particular, significant advancements have been made in identifying and quantifying the historical change in global reservoirs at a 0.01 to 100 km^2 resolution (Donchyts et al., 2022). In addition, the temporal analysis of lakes extents has been analyzed up to 50 degrees North at a 0.1 km^2 resolution (Khandelwal et al., 2022). The identification of natural lakes in high latitude regions has not been analyzed within a global water surface change context.

Far fewer studies have analyzed the change of river extents. Allen and Pavelsky (2018) mapped the observed global surface area of rivers but only for a specific year and at mean annual water discharge. More recently, Feng et al., (2022) quantified the temporal variability in global river widths over the past 37 years based on 30 m Landsat imagery. However, this study does not map the changing surface area of rivers nor provides measurements at the confluence and divergence of rivers common in anabranching and braided systems that comprise an estimated 52% of global rivers (Nyberg et al., 2023). As a result, there remains a significant knowledge gap in the temporal variability of river surface area and its interaction with lakes and reservoirs. The aim of this paper is to compile existing information to map the historical change in water surface area for rivers and lakes over the past 38-years, and to examine the implications for water resource management, ecosystem health and biogeochemical cycles.

2. Materials and Methods

2.1 Water Surface Area Classification

To classify the permanent and seasonal extent of lakes and rivers, we utilize existing datasets describing the surface area of water combined with a new and improved definition of river extents on a global scale. Our analysis is based on the Global Surface Water (GSW) model by Pekel et al. (2016) that describes the permanent and seasonal extent of open water from 1984 to 2023 based on 30 m Landsat imagery. Permanent surface area of water is defined as locations where open water is detected for all twelve months of a given year (or 100% of valid pixels). Seasonal surface water was defined as any pixel location with at least one month during which water was detected. The authors report less than 1% false positive open water classifications and less than 5% missed open water classifications based on 40,000 randomly selected points.

To define the spatial extent of rivers is challenging given the dynamic nature of rivers, varying morphology, and perennial versus non-perennial character of rivers. Nyberg et al. (2023) quantified the global extent of river channel belts (GCB) based on 30 m resolution Landsat imagery using a machine learning method that spatially delineates channel belt areas based on geomorphological properties. The river channel belt extents show the riverine landforms of the river channel and its associated levees, bars and overbank deposits that therefore capture the evolution of the riverine environment over time (Figure 1). The model reports a confidence value ranging from 0 to 100%, where a 0% confidence value indicates a non-riverine environment whereas a 100% confidence indicates a riverine environment for a given pixel location. An evaluation of this model reported a 94% accuracy to the validation dataset for channel belts wider than a 1 km. By combining the GCB and GSW datasets, we produce a new global dataset mapping the historical change of the seasonal and permanent water surface area of lakes and rivers (SARL) from 1984 to 2023. The seasonal extent of water within the channel belt shows rivers at bankfull or larger flood events with inundation persisting for at least one month. Waterbodies outside the channel belt are defined as a lakes or wetland regions that represent a body of water outside the delineated river channel belt extents (Figure 1).

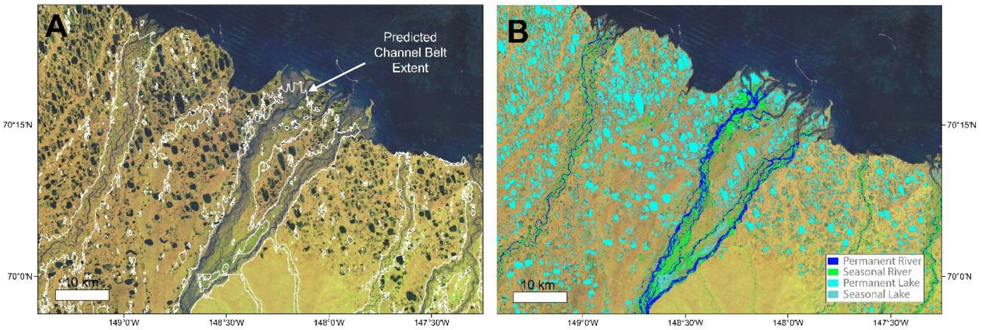

Figure 1: Example permanent and seasonal water extent in rivers and lakes - A) Example Landsat 8 imagery for 2020 with overlain delineations of the maximum channel belt extent in white based on the GCB model (Nyberg et al., 2023). Any pixel outside the channel belt is defined as lacustrine/wetland or floodplain. B) Change in permanent water extent from 1984 to 2020 based on the GSW model (Pekel et al., 2016). Combined the two datasets provide a definition of the seasonal and permanent change of water in riverine and lacustrine environments. Landsat imagery courtesy of the USGS. See interactive map for further detail.

To improve delineations of river channel belt extent we refine the classification of Nyberg et al., (2023) by utilizing a 10% confidence on the GCB prediction below 60 degrees North and a 50% confidence above 60 degrees North. This step was chosen to constrain rivers without distinct channel belts in high latitude regions (e.g., Canadian Shield or Siberian Plateau) given most sedimentary basins with clearly defined channel belts occur around mid to

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low latitude regions (Nyberg and Howell, 2016). In addition, previous databases of large lakes and reservoirs (~ > 10 km^2) defined by the HydroLakes (Messager et al., 2016) and OpenStreetMap (2022) datasets were included to further improve delineations. The inclusion of the lacustrine databases reduced the global channel belt extent by 1.86% or 13.4 x 10^4 km^2. These steps were processed on the Google Earth Engine platform (Gorelick et al., 2017) resulting in a global database of the seasonal and permanent surface area of rivers and lakes from 1984 to 2022 at a 30 m Landsat resolution.

2.2 Temporal Water Surface Area Analysis

Following the mapping of the SARL database, we analyze the data by aggregating results on drainage catchments derived from the HydroSHEDS level 5 catchment dataset (Lehner et al., 2008). Considering that satellite imagery is not available for certain years due to non-acquisition or excessive cloud cover, it is important to consider missing values in the time series of surface water observations. Pekel et al., 2016 define the location of missing values for each year in the GSW database but do not identify the waterbody type or seasonality of those missing values. To rectify this omission, we take the averaged ratio between seasonal to permanent waterbody extent between 2015 to 2017 for each catchment as a baseline given there are no reported missing values during those years. Subsequently, for each catchment the permanent and seasonal water extent for each time period without satellite data is calculated proportional to number of missing values and known ratio of seasonal to permanent extent in equation 1.

$$pArea = pO + \left(nD * (1 - k)\right) \quad if\ nD * \frac{1-k}{p} < 0.05 \qquad \text{(1a)}$$

$$sArea = sO + (nD * k) \quad if\ nD * k < 0.05 \qquad \text{(1b)}$$

where pArea is the permanent surface area, sArea is the seasonal surface area, pO is the observed permanent surface area, sO is the observed seasonal surface area, nD is the number of no data values for the entire catchment, k is the seasonal:permanent surface area ratio and p is the total number of water pixels (e.g. observed + missing values).

Equation 1 is processed separately for rivers and lakes and only assigned to catchments where less than 5% of the data is missing for any given year, waterbody type and seasonality. For years with more than 5% missing values, the first year with valid observations for any given catchment is used. This creates an accompanying dataset showing the absolute change, percentage change and annual percentage change in surface area of waterbodies for each catchment from 1984 to 2022 (see Data Statement section for interactive map and supplementary figure S1). While this approach does not account for the changing seasonal to permanent water ratios, it does provide an approximation that allows for the analysis of water trends in situations where a few missing values are reported in a much larger catchment region.

To statistically analyze trends in the surface area of rivers and lakes by catchment, we perform Spearman rank correlations (Spearman, 1987). This correlation measures the monotonicity of the relationship between two parameters, in this case the surface area of the waterbody extent versus time. This measure is ideal considering waterbody extent is often not a linear relationship with time given the interannual variability. To perform this analysis, we limit our analyses to catchments with more than 10 years of results, at least 1km^2 of detected water surface area, and 95% data coverage for each year. Statistically significant trends are defined by p value less than 0.05 or 5%.

2.3 Validation

To validate and assess the accuracy of the SARL dataset over the 38-years of available water surface change data, we compare the results to manually interpreted extent of river channel belt and lake environments for the year 2022. In total, 50 locations (see supplementary material Figure S2) measuring 50 km^2 were randomly selected (excluding Greenland and Antarctica) to manually map the river channel belt extent using 30 m Landsat 8 imagery. The Landsat imagery corresponds to the same spatial resolution and year of acquisition as the GCB dataset defined by Nyberg et al. (2023) which is used in the current model to define the global channel belt extent (section 2.1). The manual delineation of the channel belt is defined as the encompassing region of the active river and its associated bars, over bank deposits and abandoned channels (Nyberg et al., 2023) to show the maximum geomorphologically-observed extent of the river system through time.

Following the proposed automated method to classify the current SARL database (e.g., Figure 1), waterbodies defined within the manually defined channel belt extent are classified as riverine whereas all other surface water bodies are defined as lacustrine. Seasonal and permanent waterbody extent for both rivers and lakes are then extracted based on the GSW model (Pekel et al., 2016). The manual river channel belt delineation is subsequently used to compare the accuracy of the automated delineation in capturing the permanent and seasonal water extent of the GSW dataset from 1984 to 2023 (see supplementary Table S2). While the GCB delineation is currently only available for the year 2022, the method provides a baseline assessment for the accuracy of the automated method in capturing the natural variability in seasonal and permanent water extent through time.

3. Results

3.1 Total Water Surface Extent

The permanent surface area of rivers has remained relatively steady over the past 38 years, increasing slightly by 1.1% to a total area of 2.9 x 10^5 km^2 (Figure 2A). In contrast, the observed seasonal extent of rivers has increased more significantly by 12% with a total area of 3.2 x 10^5 km^2 by 2022. The yearly percentage of seasonal to permanent river water extent ranges from 88 to 119%, increasing towards the end of 2022. Similarly, the spatial extent of permanent lake surface area has increased by less than 1% since 1984 to a total area of 24.2 x 10^5 km^2 (Figure 2B). The seasonal extent of lakes has however increased significantly, by as much as 27% since 1984 to a total area of 7.2 x 10^5 km^2. The ratio of seasonal to permanent water change in lakes is considerably lower than that of rivers, and ranges between 23-31% over the same period.

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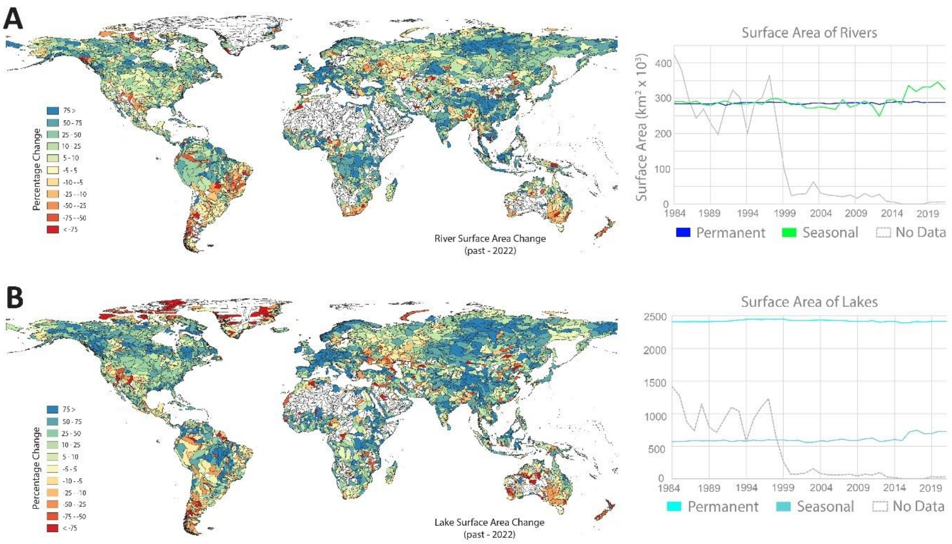

Figure 2: Global Water Surface Area Change - The global surface water area of rivers (A) and lakes (B) based on the difference between the first recorded observation to 2022. Graphs show the temporal variability in permanent and seasonal water extent of rivers and lakes by year. See supplementary Figure S3 for percentage change by permanent and seasonal river and lake levels.

3.2 Annual Water Surface Area Trends

Figure 3 show trends in permanent versus seasonal water surface area of rivers and lakes from 1984 to 2022 based on the Spearman rank correlations. Rivers and lakes show a relative normal distribution in spearman correlations indicating permanent extent of rivers and lakes have experienced both decrease and increase in surface water area. In total, 47% and 54% of catchments show the permanent surface area of rivers (Figure 3A) and lakes (Figure 3C) have statistically changed. Out of all catchments with statistically significant changes, 60% and 54% of catchments have a positive increase in permanent water surface area for rivers and lakes, respectively. In comparison, the seasonal extent of rivers and lakes is strongly positive indicating an overall increased seasonality with 42% and 49% of catchments showing a significant change for rivers and lakes, respectively (Figure 3B and 3D). Out of all catchments with statistically significant changes, 84% and 90% of catchments have a positive increase in seasonal water surface area extent for rivers and lakes, respectively.

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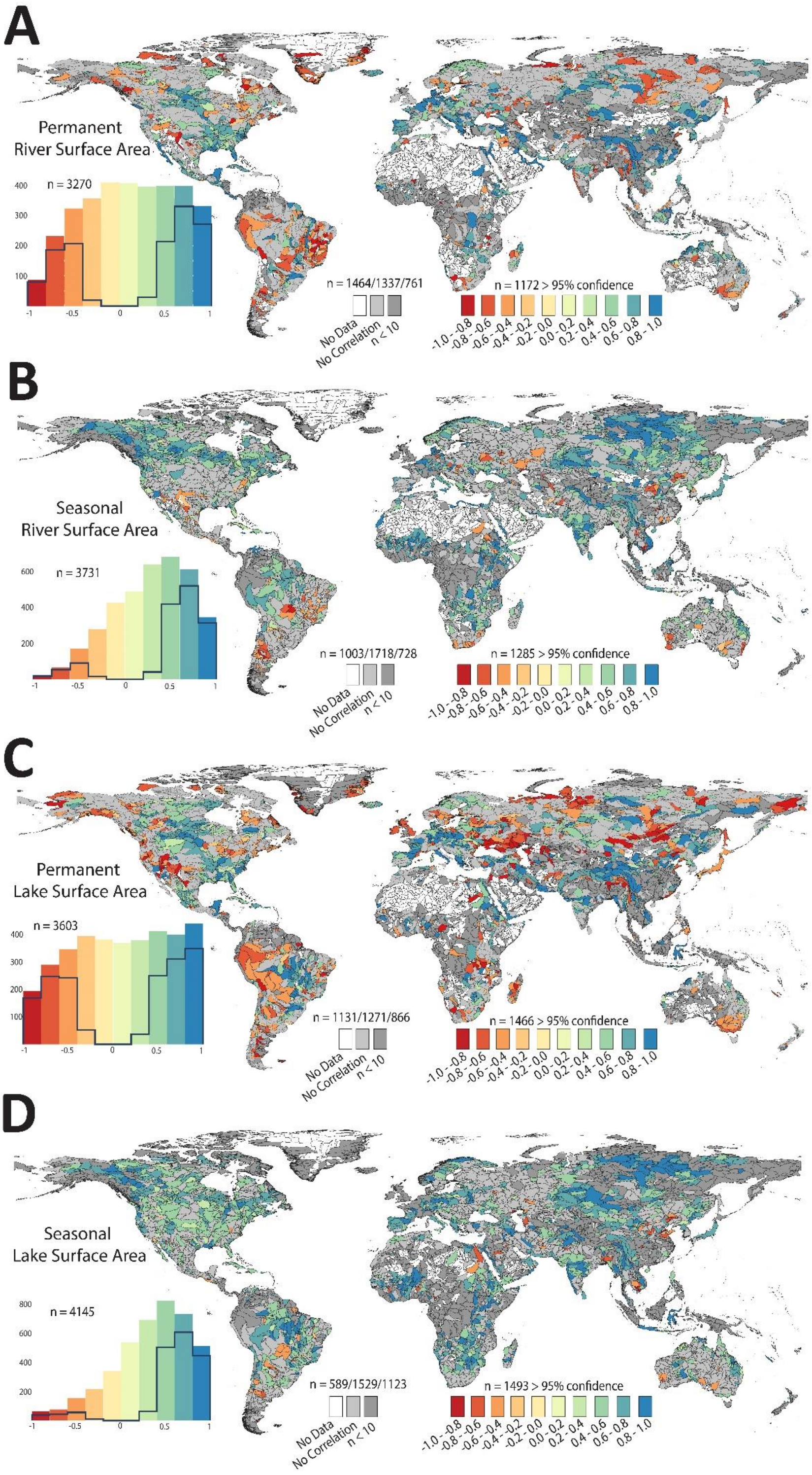

Figure 3: Spearman Rank Correlations: Catchments with statistically significant change in permanent (A,C) and seasonal (B,D) water surface area since 1984 to 2020 for rivers and lakes. Spearman rank correlations are shown ranging from -1 (red) to 1 (blue) where no correlation (light gray) indicate no statistically significant change. The histogram for each map shows the spearman correlations with the line indicating the distribution of the statistically significant samples (n > 9). See supplementary Figure S4 for entire spearman correlation dataset.

3.3 Accuracy

Overall, the SARL dataset showed a 93.8% accuracy to independent estimates of permanent and seasonal lake coverage over the 38-year period as summarized in Figure 4. The permanent extent of lakes is the most consistent and has the highest accuracy ranging between 96 and 98 percent. The accuracy of the permanent river extent is the lowest and ranges from 84 to 91%. Finally, both the seasonal river and seasonal lakes waterbodies show on average an accuracy over 90% but are also the most variable reflecting the variability in yearly water extent.

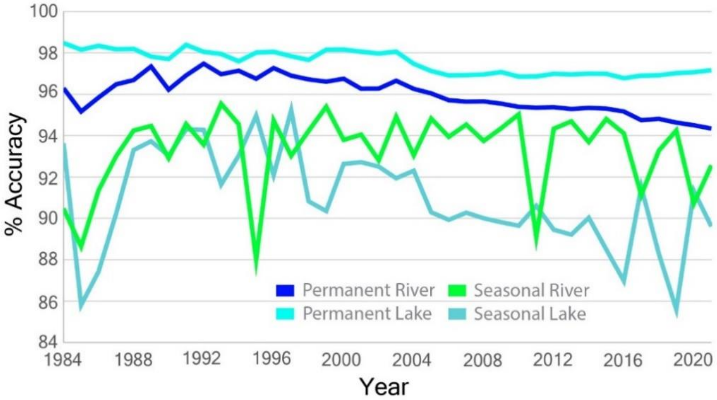

Figure 4: Temporal Accuracy of the SARL Database - Overall accuracy of the SARL database for seasonal and permanent water extent of lakes and rivers.

4. Discussion

4.1 Ecosystem Health

Understanding temporal and spatial changes in rivers and lakes is key to the study of animal migrations and community dynamics in and around lotic and lentic environments (Ngor et al., 2018). The availability of spawning pathways from ocean to permanent mainstem rivers and lakes to permanent or seasonal tributary streams and lakes is obviously a function of water presence and quality (Briggs et al., 2018). Site selection by aquatic organisms of preferred habitat for feeding and nutrients will also depend on whether or not water is present at candidate locations

(Power et al., 2008). In general, riverine and lacustrine animals move in response to changing water extents, so the ability to determine or predict the occurrence of water in global rivers and lakes is a powerful capability.

The ability to couple the area of river and stream surface water with adjacent, in-channel terrestrial area supports increased understanding of freshwater microhabitats and freshwater biotic interactions. For example, while fish are obviously restricted to in-water lotic microhabitats like riffles, pools, and runs (whose locations also change spatially and temporally with changing surface water extent), amphibians and certain terrestrial invertebrates regularly move between water and adjacent in-channel dry land (Lowe, 2009). Conceptualizing and delineating freshwater ecosystems as only containing water is therefore under-representative of the area of occupancy and use by many freshwater aquatic organisms.

Certain areas in the aqueous stream channel are utilized as flow refugia (Lancaster and Hildrew, 1993; Sakai et al., 2021) or refugia from adverse stream acidification episodes (Baker et al., 1996) during discharge events. The availability of flow refugia is a function of riverine surface water seasonality (Lancaster and Hildrew, 1993). Clearly, the ability to bound the riverine environment as not just the water but the larger area within the channel belt, and then to be able to distinguish between water and adjacent dryland spatially and temporally within that riverine ecosystem, will advance understanding of the distribution and behavior of aquatic organisms in seasonally changing environments. Moreover, current biodiversity models often overlook the importance of terrestrial and aquatic ecosystems in non-perennial systems (Messager et al., 2021). The current datasets may help to narrow this knowledge gap.

The delineation of channel belt areas as geomorphologically-derived riverine environments also has potential for addressing the 'linearity' challenge when delineating global freshwater ecosystems and habitats. For certain applications like ecosystem conservation status reporting (e.g. such as is required by the UN Convention on Biological Diversity) and ecosystem accounting (such as is characterized in the guidance from the UN's System for Environmental and Economic Accounting), area-based measures of ecosystem extent are needed. Except for very large rivers, however, river features are nearly always represented spatially as vector networks where the spatial entity for a river reach is a line segment. The segments may have an attribute for river width, but regardless, the spatial entities representing river reaches are generally not area-based, and including freshwater ecosystems in area-based assessments is challenging. As such, there may be utility in using the Global Channel Belt resource for the spatial delineation of global freshwater ecosystems which would permit area-based assessments of their condition.

4.2 Biogeochemical cycles

Existing observations of river surface area at a 30 m global resolution suggest an area of 4.6 x 10^5 km at mean annual water discharge (Allen and Pavelsky, 2018). However, our current study at the same 30 m resolution suggests that the permanent extent of rivers is considerably lower at 2.9 x 10^5 km^2 or 37% less (Figure 2). On the other hand, the seasonal extent of rivers may contribute another 3.2 x 10^5 km^2 for a total area of 6.1 x 10^5 km^2 or an area approximately 32% larger than the previous observed estimate. Given rivers are known as a significant source of carbon emissions through water-atmosphere controls, our observations suggest a strong seasonal influence on biogeochemical cycles. Indeed, current estimates based on modelled monthly river surface area suggest that rivers emit 2.0 ± 0.2 Pg C y^{-1} and that it is strongly based on seasonal river extents, particularly in temperate and arctic rivers (Liu et al., 2022). The current study furthermore suggests that rivers have, over the past 38 years, increased in seasonality by as much as 12%. This entails that carbon emissions from rivers have significantly increased in recent years, especially from high latitude Arctic rivers and high mountainous regions, of for instance, the Tibetan Plateau that experience longer summer months.

The type of river system is also important in the carbon cycle with high discharge braided rivers recognized to actively erode carbon rich floodplain material to reduce carbon oxidation into the atmosphere (Repasch et al., 2021). The current SARL database show locations of laterally active river systems versus human-controlled river systems. It is also important to recognize the perennial versus non-perennial nature of rivers and lakes which suggests that CO^2 emissions from dry inland waters is overlooked in global calculations contributing an additional 6% (~0.12 Pg C y^{-1}; Keller et al., 2020; Messager et al., 2021). The decreasing permanent extent of many lakes and rivers (Figure 2) suggest that previously buried sediments with a disproportionately high amount of organic carbon will be increasingly released to the atmosphere (Keller et al., 2020; Hao et al., 2021). Lastly, the damming of rivers and its impact on flow and sedimentation patterns have been shown to eliminate another 48±11 Tg C y^{-1} (Maavara et al., 2017), although there remain significant knowledge gaps at the local to regional level. The current study and recent reservoir maps (Donchyts et al., 2022; Khandelwal et al., 2022) highlight that rivers and reservoirs have undergone significant historical changes, which may help to further constrain these estimates.

4.3 Water Resource Management

Global observations of surface water extent are important to regulate and manage water at a basin scale for a range of different sectors including agriculture, ecosystems, forestry, energy, water supply, environment protection, flood and drought control, irrigation, wastewater treatment, governance and policy to name a few (Garcia et al., 2016; Sheffield et al., 2018). In particular, the data is important to understand the impacts of hydrological extremes of droughts and floods on the short and long-term trends on water allocation and management. The distinction of rivers and lakes is important to understand the storage and transfer of water that impact different sectors and to predict the future impacts of human and climate change stressors.

The permanent versus seasonal extent of water is also important to quantify pressures on water resources. In many circumstances, the permanent extent of rivers and lakes has decreased over the past ~4 decades of observations and replaced by an increased seasonality (Figure 3, Pekel et al., 2016; Donchyts, et al., 2016). A change from perennial to seasonal surface water of river directly impacts groundwater recharge and the resulting water table level (Gleeson et al., 2020). For instance, regions of central Australia, Caspian Sea, Aral Sea, western United States, and southern Africa have seen a statistical decrease in permanent waters of both rivers and lakes (Figure 2) that are related to well documented droughts and anthropogenic stresses (Micklin et al., 2007, Van Loon et al., 2016; Mekonnen et al., 2016). There are also rivers that while have experienced relatively stable permanent river water levels, also show decreased annual seasonal flooding, of for example, the Ob River in Siberia (Zemtsov, 2019).

On the other extreme, the Brahmaputra River in Bangladesh and India show an increase in the seasonal extent (Figure 2) that is attributed to increased intensity of river discharge during monsoonal seasons due to increasing Southern Oscillation Index extremes (Mirza, 2011). In other natural river systems, like the lower Amazon basin, we see a slight, statistically significant increase in water surface area of rivers over past three decades (Figure 3). The Amazon water catchment as one of the least human-modified river systems globally (Grill et al., 2019), has increased water levels due to a strengthening Walker circulation (Barichivich et al., 2023). An increase in permanent water surface area for both rivers and lakes is particularly noticeable in central Asia and the Tibetan Plateau as well which has been associated with the acceleration of glacial melting and precipitation (Bo Huang, 2014). Furthermore, seasonal water expansion in Siberia can be related to increased thawing of permafrost lakes in summer months (Matthews et al., 2020). Lastly, reservoir expansion, particularly around the Indian subcontinent, eastern Brazil and China, attribute to the increased water surface area of lakes (Donchyts et al., 2022).

5. Conclusions

Here we have presented a new classification on the long-term change in permanent and seasonal extents of both rivers and lakes from 1984 to 2022. Our results show that while the global area of permanent rivers and lakes has remained relatively steady over the past 4 decades (~1% change), the regional variability is considerably higher. The global extent of seasonal rivers and lakes present a different trend, increasing in surface area by 12% and 27%, respectively. For catchments with a statistically significant change, 84% are positively skewed showing an increased seasonality in surface water coverage over the same period. The decreasing perennial extent of many rivers and lakes is often reflected in an increased seasonality of those same water bodies. The results of our analysis are shared as the SARL database, which includes waterbody type, seasonality and spatio-temporal change for global rivers and lakes. This database is a valuable resource and framework for water resource monitoring and assessment of ecosystem health and conservation in different waterbody types.

Data Availability

The SARL database developed in this study have been deposited in the Zenodo database under accession code https://doi.org/10.5281/zenodo.6895820. An interactive map is available at https://bjornburrnyberg.users.earthengine.app/view/waterchange

Author Contribution

BN conceived the original idea, designed the methodology and created the database. BN and EL analyzed the original data and created the figures. BN, RS and EL wrote the manuscript.

Competing interests

The authors declare that they have no conflict of interest.

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