

Rivers as political borders: a new subnational geospatial dataset

Sarah J. Popelka^{a,*} and Laurence C. Smith^{a,b,c}

^a*UCLA Department of Geography, University of California, Los Angeles, CA 90095, USA*

**Corresponding author. E-mail: sarah.popelka.86@gmail.com*

^b*Institute at Brown for Environment and Society, Brown University, Providence, RI 02912, USA*

^c*Department of Earth, Environmental and Planetary Sciences, Brown University, Providence, RI 02912, USA*

Abstract

Rivers are commonly used to define political borders, but no global study has quantified the importance of rivers on territorial delimitation at subnational scales. This paper presents Global Subnational River-Borders (GSRB), a first comprehensive geospatial dataset of subnational, as well as national, political borders set by large rivers. GSRB incorporates three previous vector datasets (GAUL, GRWL + +, and WDBII) to map and quantify the use of large rivers as political borders at local, state, and national scales. GSRB conservatively finds that at least 58,588 km (23%) of the world's interior (non-coastal) national borders, 199,922 km (17%) of the world's interior state/province borders, and 459,459 km (12%) of the world's interior local-level political borders are set by large rivers. GSRB finds 222, 2,350, and 14,808 dyads sharing river-borders at these three administrative scales, respectively. While previous studies have emphasized transboundary rivers separating nations, GSRB highlights the abundance of river-borders at subnational scales, where numerous domestic stakeholders share jurisdiction in water resource management. These participants, identified with GSRB, ought not to be ignored when crafting water policy and instituting whole-basin management regimes. GSRB should prove useful for global, geospatial analyses of riparian stakeholders across administrative scales. The GSRB dataset (DOI: 10.5281/zenodo.3906566) can be found via the following link <https://zenodo.org/record/3906567#.XvN-GGhKjIU>.

Keywords: GIS; Hydropolitics; River-border; Subnational; Transboundary rivers; Water resource management

Introduction

Our territorially delimited world lies at odds with increasing global interconnectedness, creating challenges for transboundary water policy. Tensions exist between calls for a 'post-border' world and heightened conflict over territoriality (Newman, 2006; Matthews & St. Germain, 2007; Jones, 2009; Paasi, 2009). In water resource management, borderless governance frameworks materialize in the form of basin-scale management regimes (Newson, 1997; Earle *et al.*, 2010; Venot *et al.*, 2011;

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Grech-Madin *et al.*, 2018). These whole-basin approaches unite riparian states around the river drainage area as a unit of management, creating supra-national governance structures meant to enable cooperation and adjudication of thorny issues surrounding transboundary water supply, regulation, and management (Zawahri *et al.*, 2011; Thomas, 2017). Recent case studies of hydropolitics and resource allocation in federal states present a clash between centralized or extranational cooperative governance and the autonomy and self-interest of subnational units as independent governing bodies (Garrick *et al.*, 2013; Moore, 2017; De Stefano & Garrick, 2018). As such, despite post-border rhetoric, political borders remain distinct realities, given humanity's desire to control and delimit landscapes. Modern societies are defined by territoriality, sovereign states, and abrupt, linear borders. A large body of the literature discusses the use of a physical line (represented cartographically and enacted on the ground) as a necessity for conceptualizing and communicating the extents of spaces and the creation of national identities (Branch, 2011; Cameron, 2011; Allouche, 2019). Such lines on the ground have direct implications for the well-being of the polity, as well as the realities of numerous social and political structures and issues (Branch, 2011). Therefore, even as some scholars advocate transcending boundaries, borderlands studies have seen a revitalization, particularly in terms of 'boundary demarcation, delimitation, and management' (Newman, 2006), i.e. the processes by which a boundary becomes visible, indisputable, and impassable. Of course, where and how boundaries are drawn greatly influences the probability and degree of conflict that the entities along them may face. Continued territorial disputes in Asia, Africa, and the Middle East, as well as a recent increase in negative reactions to immigration, are directly related to the demarcation and enactment of borders (Culcasi, 2006; Downes, 2006; Hadley, 2013; Mancini, 2013; Lamb, 2014; Culcasi, 2016; Roessler & Ohls, 2018).

Due to their inherent linearity, perceived impassibility, and the fact that they physically incise and divide the landscape, rivers have long been used as natural and supposedly egalitarian territorial delimiters between nations. Ancient empires, from the Romans to the Neo-Assyrians, used rivers as important landmarks in their written cartographies and conceptions of space, as well as physical representations of the extent of their powers (Purcell, 2012). Indigenous populations often used rivers as divisions between tribes (Osburn, 1999). In 18th century France, political leaders advanced the concept of '*limites naturelles*' ('natural frontiers'), the notion that rivers represent natural and just linear abstractions of frontier zones, in turn rationalizing France's territorial expansion (Sahlins, 1990). Indeed, French policy amply used rivers to delimit territory, and other Western European colonial powers followed suit. Similarly, both watershed divides and river channels proper were used extensively to define territory throughout the expansionist history of the conterminous United States, as mapped cartographically by Smith (2020). Many of these borders still persist today and contemporary powers across the globe continue to commonly use rivers as borders when territorial lines are redrawn.

At the international level, numerous studies have explored various aspects of the creation, realities, and challenges of river-borders. Donaldson (2009) provides an excellent and seminal overview of the themes present in the national river-border literature, including transboundary water law, the implications of international water resources on conflict, and numerous empirical case studies (Donaldson, 2009). Subsequent work has assessed effects of river-borders on the size and shape of nations (Tam, 2004; Green, 2012), the role of natural borders in affecting nation-states' development outcomes (Van Geenhuizen & Rietveld, 2002; Alesina *et al.*, 2011; Sievers & Urbatsch, 2018), and the continued impacts of climate change and resource scarcity on tensions along river-borders (Mancini, 2013; Dinar, 2014; Akhter, 2019).

In contrast to national studies, surprisingly little has been written on the use of rivers as political borders at subnational scales. One study suggests that the use of physical features, broadly, as internal borders limits conflict between peoples (Rutherford *et al.*, 2014). Another suggests that rivers as political borders lead to greater cooperation from the involved states when compared to upstream/downstream relationships (Moore, 2012). Some attention has been given to the use of topographic watershed divides in delimiting territories at subnational administrative scales. In Tuscany, for example, communities settled in valleys separated by mountains, with each valley having a distinct political and cultural identity from neighboring valleys (Pult Quaglia, 2009). A similar pattern was observed among local governance units (Manteqa) in Afghanistan, where river basins shape spatial organization and identity (Allan, 2001). In many cases, internal borders reflect core-periphery power imbalances, with urban elites seeking to exert control over and extract resources from rural lands (Fife, 2010). Legal case studies focus on the effects of shifting river courses on the states that use such waterways as territorial delimiters, for example, the use of the Missouri River as a border between the U.S. states and the resultant conflicts that arise when this river shifts course (Beck, 1967). However, no global study has comprehensively quantified the use of rivers for territorial delimitation at subnational scales.

Given the multitude of stakeholders at play in river basin management, there is a clear and pressing need to identify them at multiple geographic scales, so that all stakeholders may be considered in riparian water policy decisions (Lowi, 1995; Matthews & St. Germain, 2007; Das, 2008; Ridge, 2010; Venot *et al.*, 2011; Zawahri *et al.*, 2011; Lipscomb & Mobarak, 2016; Thomas, 2017; da Silva & Hussein, 2019). Thomas (2017), in particular, notes the role of political borders as a necessary space to consider when crafting management plans, suggesting a synergistic ‘river-border complex’, accounting for all stakeholders. Such a framework calls for a holistic view of treating rivers and political borders as intertwined systems. To approach the river-border as a system, administrative units and hydrologic features across multiple scales must be considered, a call that is sounded in numerous other papers on multiscale hydropolitical modeling and diagnostic frameworks (Garrick *et al.*, 2013; Moore, 2017; Grech-Madin *et al.*, 2018). Regardless of which framework is used to evaluate hydropolitical complexes and which policies are implemented, subnational bodies remain a potent unit of analysis since they, even more so than federal bodies, may influence the success of water resource management programs (Moore, 2012, 2017; Briscoe, 2014; Garrick & De Stefano, 2016). However, currently available spatial datasets are inadequate to support a detailed understanding of river-border complexes in the way that Thomas suggests and of the roles/interests of subnational units in the way that many of the recent papers on federal hydropolitics suggest. Global identification of subnational jurisdictions that share river-borders is notably lacking.

At least six publicly available datasets currently deal with the issue of transboundary hydrologic features (Table 1). The Encyclopedia of International Boundaries (Biger, 1995) and the Shared River Database (SRDB; Toset *et al.*, 2000) supply rich information on international river-borders, including lengths, but no explicit geospatial (locational) information. Neither provides data for subnational scales. The Transboundary Freshwater Dispute Database (TFDD; Wolf *et al.*, 1999) and The Transboundary Water Management Database (Earle *et al.*, 2010) provide explicit geospatial data but focus on catchment boundaries, rather than river-borders, and again do not provide information for subnational scales. The Global, Self-consistent, Hierarchical, High-resolution Shoreline Database (GSHHG) provides self-consistent (meaning that rivers perfectly align with borders, where they form borders) geospatial data, but not at the subnational scale, except for state borders of the United States. Those datasets exist separately as rivers and borders, rather than river-borders (Wessel & Smith, 1996).

Table 1. Currently available global datasets and databases of transboundary hydrologic features that include information on the involved political units. Thanks to newly available global datasets on subnational administrative units and remotely sensed river planforms, GSRB supplies geospatially explicit information on national, state/province, and county/local-level political borders set by large rivers.

Dataset	Year	Institution	Subnational	Geospatial	River-borders	Source
The Encyclopedia of International Boundaries	1995	Tel Aviv University	No	No	Yes	Biger (1995) . <i>The Encyclopedia of International Boundaries</i> . The Jerusalem Publishing House, Jerusalem
Global Self-consistent, Hierarchical, High-resolution Shoreline Database (GSHHG)	1996	University of Hawaii	Partially	Yes	No	Wessel & Smith (1996) . A Global Self-consistent, Hierarchical, High-resolution Shoreline Database. <i>Journal of Geophysical Research</i> 101, 8741–874. URL: http://www.soest.hawaii.edu/wessel/gshhg/
Transboundary Freshwater Dispute Database (TFDD)	1999	Oregon State University College of Earth, Ocean, and Atmospheric Sciences	No	Yes	No	Wolf et al. (1999) . International River Basins of the World. <i>International Journal of Water Resources Development</i> 15(4), 387–427. URL: http://gis.nacse.org/tfdd/index.php
Shared Rivers (SRDB)	2000	Peace Research Institute Oslo	No	No	Yes	Toset et al. (2000) . Shared Rivers and Interstate Conflict <i>Political Geography</i> 19(8), 971–996. URL: https://www.prio.org/Data/Geographical-and-Resource-Datasets/Shared-Rivers/
International River Boundaries Database (IRBD)	2009	Durham University IBRU	No	Partially	Yes	Donaldson (2009) . Where Rivers and Boundaries Meet: Building the International River Boundaries Database. <i>Water Policy</i> (11). URL: https://www.dur.ac.uk/ibru/resources/irbd/
Transboundary Water Management Database	2010	Stockholm International Water Institute	No	Yes	No	Earle et al. (2010) . <i>Transboundary Water Management: Principles and Practice</i> . Earthscan, London. URL: http://internationalwatercooperation.org/tbwaters/
Global Subnational River-Borders Dataset (GSRB)	2019	University of California, Los Angeles	Yes	Yes	Yes	This paper

[Donaldson \(2009\)](#) provides and quantifies all national river-borders with informational attributes in the explicit geospatial format as the International River-border Database (IRBD). IRBD is a truly impressive dataset, with river-borders located and digitized with painstaking precision through hand-tracing from

Google Earth imagery (Donaldson, 2009). However, Donaldson's dataset provides downloadable geospatial information for only 54% of national river-border segments and no subnational information. At the time of publication, no comprehensive, global geospatial dataset of river-borders exists for both national and subnational scales.

This paper addresses these limitations by compiling Global Subnational River-Borders (GSRB), a first comprehensive geospatial dataset of political borders set by large rivers at local, state, and national scales. First, we present the methodology used to create and quality-assured this large global dataset and describe its data structure. Next, we present a first analysis using GSRB to quantify the prevalence of river-borders at local, state, and national scales. Finally, we assess the strengths and weaknesses of GSRB relative to IRBD. We conclude that subnational river-borders are abundant across a spectrum of administrative jurisdictions and should not be overlooked in whole-basin water management regimes.

Methods

Data sources

To delineate the global distribution of large rivers, a hybridized global river map was created based on two preexisting river datasets. River planforms between 60° N and S latitudes were obtained in polyline shapefile format from Global River Widths from Landsat Plus Plus (GRWL++) (Allen & Pavelsky, 2018). This remotely sensed dataset contains river centerlines derived from Landsat visible/near-infrared satellite images and Shuttle Radar Topography Mission (SRTM) digital elevation data, as part of preparations for the forthcoming NASA/CNES/CSA/UKSA Surface Water and Ocean Topography (SWOT) satellite mission to be launched in 2021 (<https://swot.jpl.nasa.gov/>). These geospatially referenced data maintain the original 30 m resolution of the source Landsat images and confidently detect large rivers, i.e. 30 m wide and larger (Allen & Pavelsky, 2018). However, GRWL++ only extends between 60° N and S latitude, contains numerous small gaps, and lacks data where a river narrows to <30 m in width. To supplement GRWL++, additional stream polylines were obtained from the CIA World Databank II (WDBII), made available as part of the GSHHG version 2.3.7, developed and maintained by the University of Hawaii (Wessel & Smith, 1996). WDBII river planform data come in five resolutions at 10 classification levels. For this analysis, classification levels 1–4 (permanent major rivers, additional major rivers, additional rivers, and minor rivers) were used at full resolution (1:3 million scales), to yield a hybridized global river dataset containing both WDBII and GRWL++ river courses (Figure 1).

Political borders were obtained from the Global Administrative Unit Layers (GAUL) dataset (2015), implemented by FAO within the CountrySTAT and Agricultural Market Information System (AMIS) projects (<http://www.fao.org/geonetwork/srv/en/metadata.show%3Fid=12691>). These polygon shapefile data are derived from multiple data sources and represent the status of the world's national and subnational political borders as of the year 2014. GAUL provides boundaries of administrative jurisdictions at three scales: Level 0 'country', Level 1 'state/province', and Level 2 'districts/local'. We hereafter refer to these three administrative scales as 'national', 'state/province', and 'county/local' throughout this paper. With regard to disputed territories, GAUL attempts to 'preserve national integrity for all disputing countries.' GAUL represents the best currently available geospatial dataset on political border data spanning multiple administrative scales.

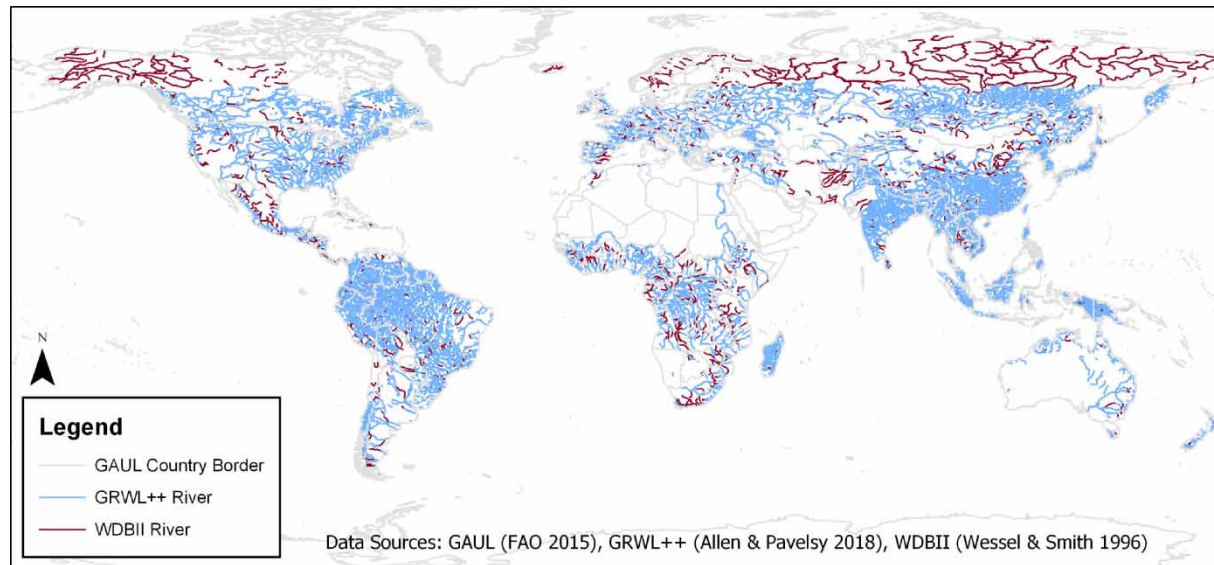


Fig. 1. Global river map merging GRWL ++ with WDBII river planform data. River segments in blue are from the remotely sensed GRWL ++ dataset, while river segments in red are WDBII river planforms not included in GRWL ++. National country-level political borders from the GAUL dataset are included (in gray) for reference. Please refer to the online version of this paper to see this figure in color: <http://dx.doi.org/10.2166/wp.2020.041>.

Finally, national river-border maps from the IRBD, University of Durham (Donaldson, 2009), were used to assess the accuracy of our methods. The IRBD river-border lengths and designations are available as spreadsheet and as KML files representing the geospatial locations of river-borders (<https://www.dur.ac.uk/ibru/resources/irbd/>). Because IRBD data are visually verified and hand-traced from high-resolution satellite imagery in Google Earth, they are deemed of high quality for this purpose.

Data processing

Data processing was performed using ESRI ArcGIS Pro Advanced software, version 2.1.0. While much of this processing was automated using Python 3.6, all work was visually monitored to ensure accuracy. The data processing stream consisted of pre-processing (deriving borders from polygon shapefiles, combining datasets, identifying units that interact with rivers, and drawing buffers), identifying river-borders (calculating locations where rivers may have driven the creation of a border), quality assurance (ensuring that the previously identified potential locations are, in fact, river-borders and that the segments are clean and complete), and statistical analysis (calculating the prevalence of river-borders, as well as estimating error), as summarized in Figure 2.

Pre-processing

Borders derived from GAUL administrative unit polygons were separated by continents, into riparian and non-riparian units, and into coastal and interior (i.e. non-coastal) borders. Continents were assigned through the intersection of GAUL polygons with an ESRI continent shapefile, and the associated continent for each administrative unit was added to the dataset as an attribute. Antarctica was not included as an administrative unit for this study, nor were its coastlines included in any global sums of border length. Next, GAUL political unit polygons were checked to assess whether they contained any large rivers as follows. GAUL polygons at each level were joined with a merged GRWL ++ and WDBII river dataset using the Spatial Join tool, with ‘intersect’ as the match option. The resulting features with Join Count values equal to zero (i.e. those for which no GRWL ++/WDBII river segments intersected) represent units that do not interact with large rivers. Features with Join Count values greater than zero represent units that do interact with large rivers. Administrative boundaries were derived from the GAUL polygons by converting administrative area polygons to lines, with neighboring polygon information stored as attribute data. Neighboring polygon information was later used to identify which polygons comprised the contiguous dyads that each border represents. The LEFT_FID output field, in which the tool stores a value of –1 for line segments that do not border another polygon, was used to determine which borders were interior borders and which borders were coastal borders, and each border type was exported to its own feature class. The result of this process was a series of border feature classes for each administrative level, where one feature class represented all coastal borders, one feature class represented all interior borders, and one feature class represented only interior borders for dyads where both administrative units involved contain a river found in the hybridized river dataset.

Since GRWL ++ data have a very different spatial resolution (30 m) and source (satellite remote sensing) than both WDBII (with an approximate working scale of 1:3 million) and GAUL data (which combines a variety of spatial resolutions, depending on the source of the unit boundaries), overlaying the two datasets produces abundant cartographic mismatches in co-registration and line shapes

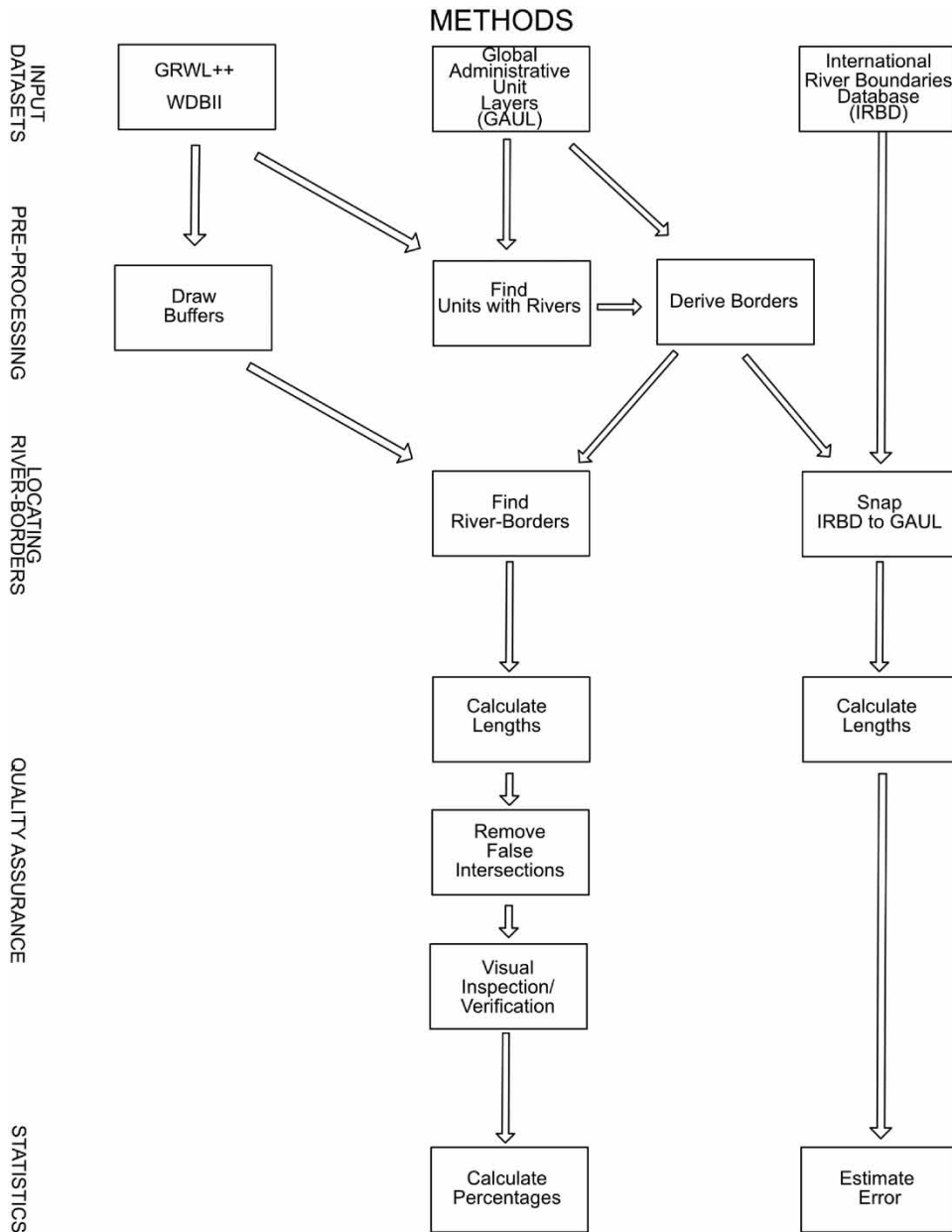


Fig. 2. Flowchart summarizing the data processing and statistical methods used in this paper. Each category on the left-hand side represents a subheading in the methods section, with each box representing a step or collection of steps detailed within each subheading.

(Figure 3). These mismatches confound simple intersections between the disparate datasets, as the features do not align closely in space or shape. This problem was resolved by separately buffering GRWL ++ lines and WDBII lines using a 2 km radius calculated using geodesic distance. Buffering

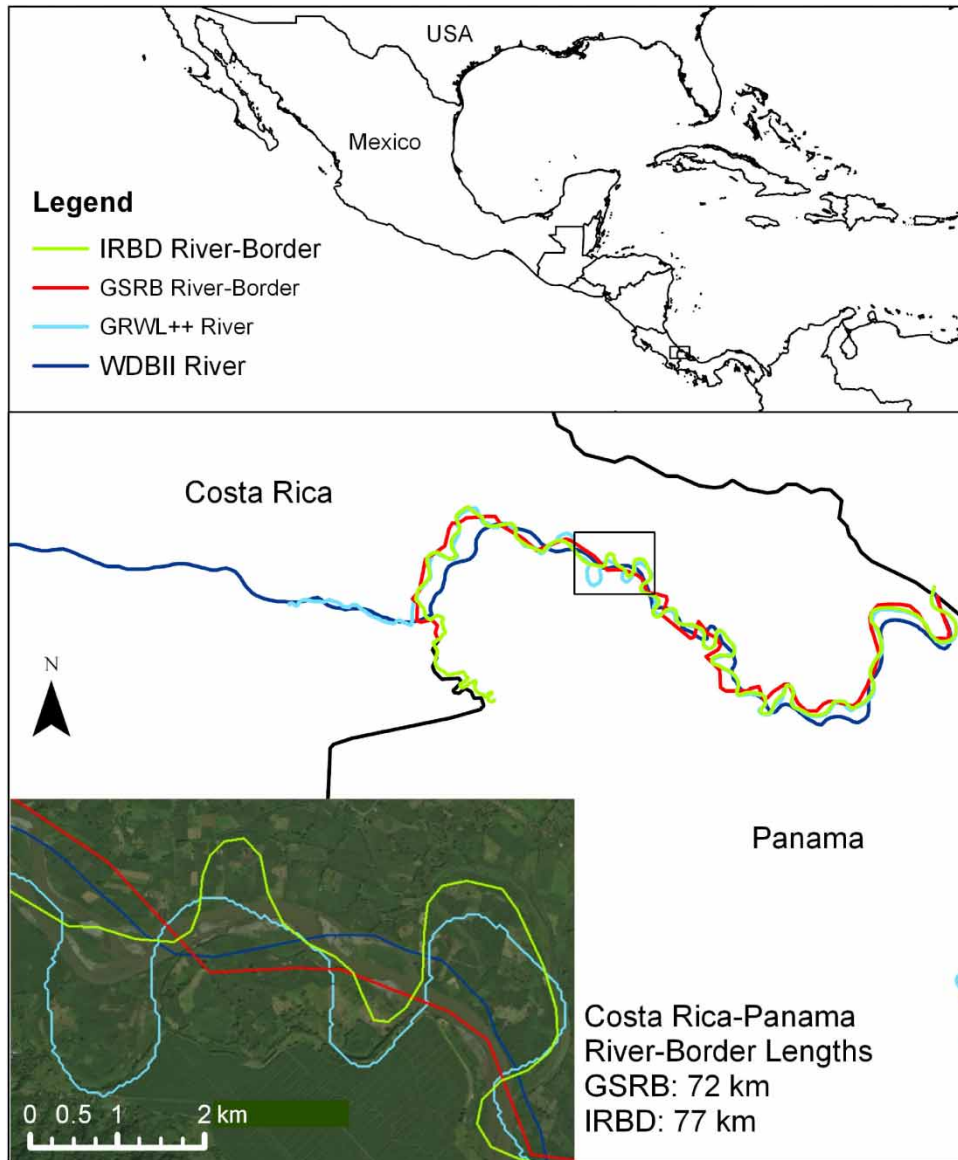


Fig. 3. Example of geospatial data mismatch between input datasets along the border between Costa Rica and Panama. Green lines represent IRBD river-border segments, red lines represent GSRB river-border segments (as derived from GAUL), light blue lines represent GRWL++ rivers, and dark blue lines represent WDBII rivers. Note the difference in derived river-border lengths between GSRB and IRBD calculations, and cartographic mismatches between all four datasets. To mitigate such mismatches, we applied a 2 km buffer to all GRWL++/WDBII river segments in the creation of GSRB. Satellite imagery source: ESRI World Imagery Basemap. Please refer to the online version of this paper to see this figure in color: <http://dx.doi.org/10.2166/wp.2020.041>.

river planforms serves the additional purpose of accounting for the uncertainty inherent in attempting to record the location of a river, given the dynamism of watercourses, which can change rapidly. Buffering in such a way suggests that a watercourse may be found within the given polygon, rather than restricting

a river's location to a point-in-time linear snapshot. An optimal buffering value of 2 km, which produced a high ratio of true river-borders to spurious intersections, was decided upon after stepwise trial and error, based on Euclidean distances between the datasets, derived manually in ArcGIS Pro.

River-border identification

Intersections between political borders and rivers were identified to create the new GSRB dataset. Additionally, river-borders previously identified in IRBD were located in the GAUL dataset, so that the lengths of those segments as measured by Donaldson (2009) could be compared to the lengths of corresponding segments as measured by GSRB. The interior border feature classes for each GAUL administrative level were clipped to the aforementioned 2 km river buffers from GRWL ++ and WDBII, to obtain a new feature class containing any political border segment occurring within 2 km of a GRWL ++ or WDBII river. Separately, IRBD river-borders were snapped to the vertices and edges of all GAUL polygons using a 3 km search radius, such that the resultant IRBD lines took the shape of the polygons and represented river-borders with the same location and geometry of GAUL borders. This additional step allowed us to quantify the reduction in resolution and border lengths that can result from using the GAUL border dataset to calculate river-borders in an automated fashion, rather than hand-tracing Google Earth imagery.

Quality assurance

Intersecting high-resolution remotely sensed river planforms with lower resolution vector political border datasets produces numerous spurious intersections. These include locations where a political border crosses a river but does not follow it, which must be separated from the many true alignments between rivers and borders that this project seeks to identify (Figure 4). Through trial and error, we determined that spurious intersections typically have characteristically short length scales (<5 km) and few vertices, as they tend to follow straight-line segments or locations where the river is perpendicular to a border. To remove spurious intersections, the geodesic length was calculated for all intersected line segments, and any segment having a geodesic length shorter than 5 km and fewer than 4 vertices was removed. Additionally, the sinuosity of the border segments was calculated (segment length divided by the Euclidean distance between its start and end points) and segments having sinuosity <1.03 were removed. Two kilometers were removed from either end of river-border segments, except for ends, which were also the end of the border segment. Following these automated procedures, further manual edits were made to the dataset in ArcGIS based on visual comparisons of derived intersections with the ESRI satellite basemap. Border segments were compared across administrative levels and added or trimmed, as appropriate, to ensure consistency across levels. Following these quality-assurance steps, the geodesic lengths of the new, quality-assured border segments were calculated and remaining river-border segments with lengths less than 2 km were removed from the dataset, except where those segments were the entire length of the border and occurred between two other river-border segments. In the latter case, river-border segments with lengths less than 1.5 km were removed. The resulting segments were dissolved by dyad. Final geodesic lengths for each dyad were incorporated as attribute data in GSRB.

Where available, other attribute data were also added to the GSRB dataset. These attributes include names of administrative units sharing a river-border at relevant administrative levels as derived from

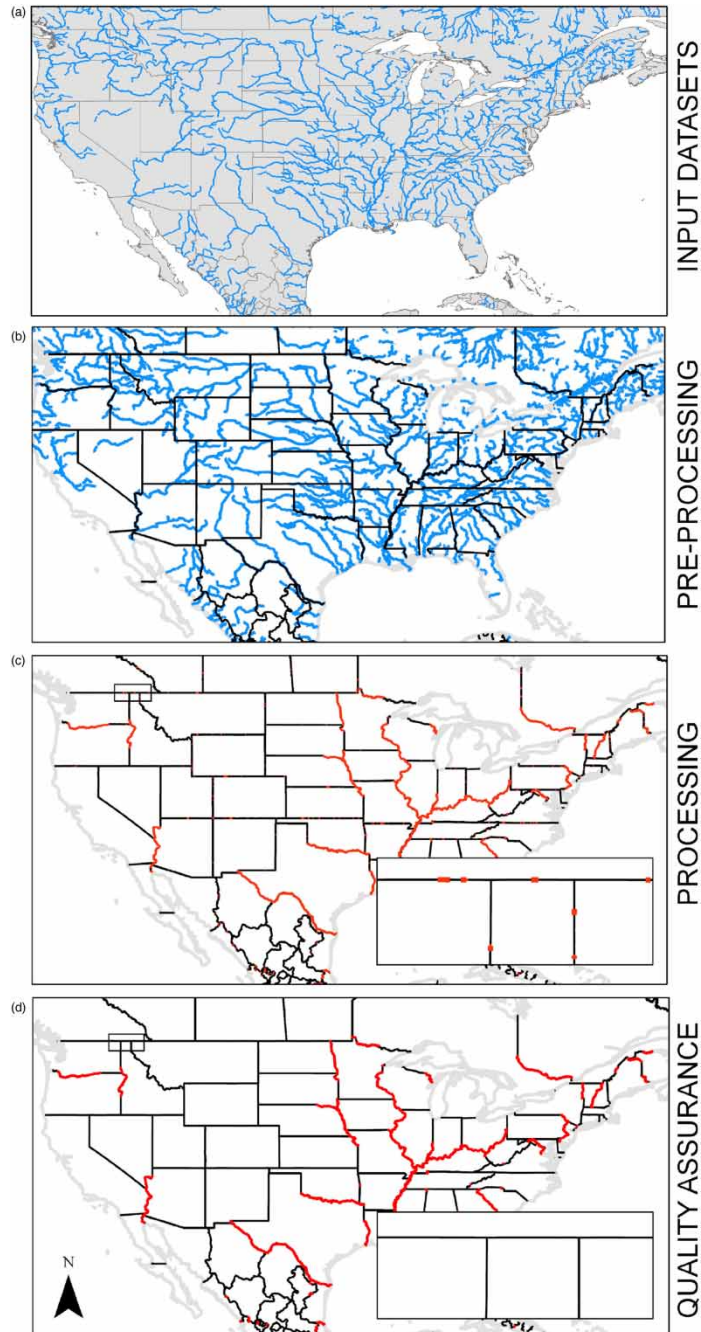


Fig. 4. United States rivers, state-level political borders, and state-level river-borders as calculated in GSRB: (a) GAUL Level 1 interior political unit polygons (shaded in gray) and GRWL + +/WDBII river planforms (in blue); (b) after pre-processing – GAUL-derived coastal borders (in gray), GAUL-derived Level 1 interior borders (in black), and buffered GRWL + +/WDBII river planforms (in blue); (c) after locating river-borders (in red); and (d) after quality-assurance. The insets in panel (c and d) illustrate the removal of spurious intersections (here, short red segments along a latitudinal border) that were incorrectly classified as river-borders. Please refer to the online version of this paper to see this figure in color: <http://dx.doi.org/10.2166/wp.2020.041>.

GAUL (i.e. the two countries for Level 0, the two state/provinces and corresponding countries for Level 1, and the two counties and corresponding states/provinces and countries for Level 2), as well as the corresponding continent. The finished vector data product and associated attribute tables are GSRB (Figure 5). The GSRB dataset (DOI: 10.5281/zenodo.3906566) can be found via the following link <https://zenodo.org/record/3906567#.XvN-GGhKjIU>.

Statistical calculations

To quantify the influence of coastlines on political border formation, the lengths of coastal borders were summed and divided by the total length of borders at each administrative level, for each continent, with coastal lengths reported as percentages of total border lengths to normalize across scales. To quantify the overall use of large rivers for political border formation, the lengths of GSRB river-border intersections were summed and divided by the total lengths of all borders for each continent at each administrative level. These measures were reported as percentages of total border lengths in three ways: (a) all borders; (b) all interior (non-coastal) borders; and (c) only those interior borders of administrative units containing large rivers. With few exceptions (e.g. Greenland, Libya, and Saudi Arabia), this last category is applicable mainly to smaller administrative scales (i.e. state/province and county/local) (Level 2) administrative areas, of which many (54% globally) have no opportunity to interact with a large river as represented in the hybridized GRWL + +/WDBII dataset.

Percent error was used to estimate the accuracy of the GAUL-derived river-border lengths relative to IRBD lengths. To calculate percent error, the geodesic lengths of corresponding IRBD and GAUL segments were calculated in ArcGIS, and each IRBD segment length was subtracted and normalized by the length of its corresponding GAUL-derived segment as $|(IRBD\ Length - GAUL\ Length)/GAUL\ Length| \times 100$. Median and mean values are reported.

Results

The GSRB dataset contains three levels of polyline shapefiles capturing where large rivers comprise political borders at three administrative scales. In total, the identified river-borders sum to 58,588 km at the national-level (Level 0), 199,922 km at the state/province-level (Level 1), and 459,459 km at the county/local-level (Level 2). GSRB finds 222 contiguous country dyads that share a river-border (63% of all contiguous country dyads), 2,350 contiguous state/province dyads that share a river-border (29% of all contiguous state dyads), and 14,808 contiguous county/local dyads that share a river-border (14% of all contiguous county/local dyads). If the Level 1 and Level 2 analyses are restricted to only those administrative units that actually contain large rivers, the percentages rise from 28% to 43% of state/province dyads and from 13% to 37% of county/local dyads, respectively.

Two natural features, coastlines and rivers, constitute a large percentage of the world's administrative borders. Coastlines, in particular, comprise approximately 86% of the world's national boundaries, 57% of the world's state/province-level boundaries, and 30% of the world's county/local-level boundaries. Large rivers comprise approximately 3%, 7%, and 9%, respectively (Table 2). Since coastal borders form such a large percentage of administrative boundaries, and since coastal borders, by definition, cannot also be river-borders, coastal borders are excluded from further analysis, which quantifies the influence of rivers on 'interior' (non-coastal) political borders across administrative scales. Overall,

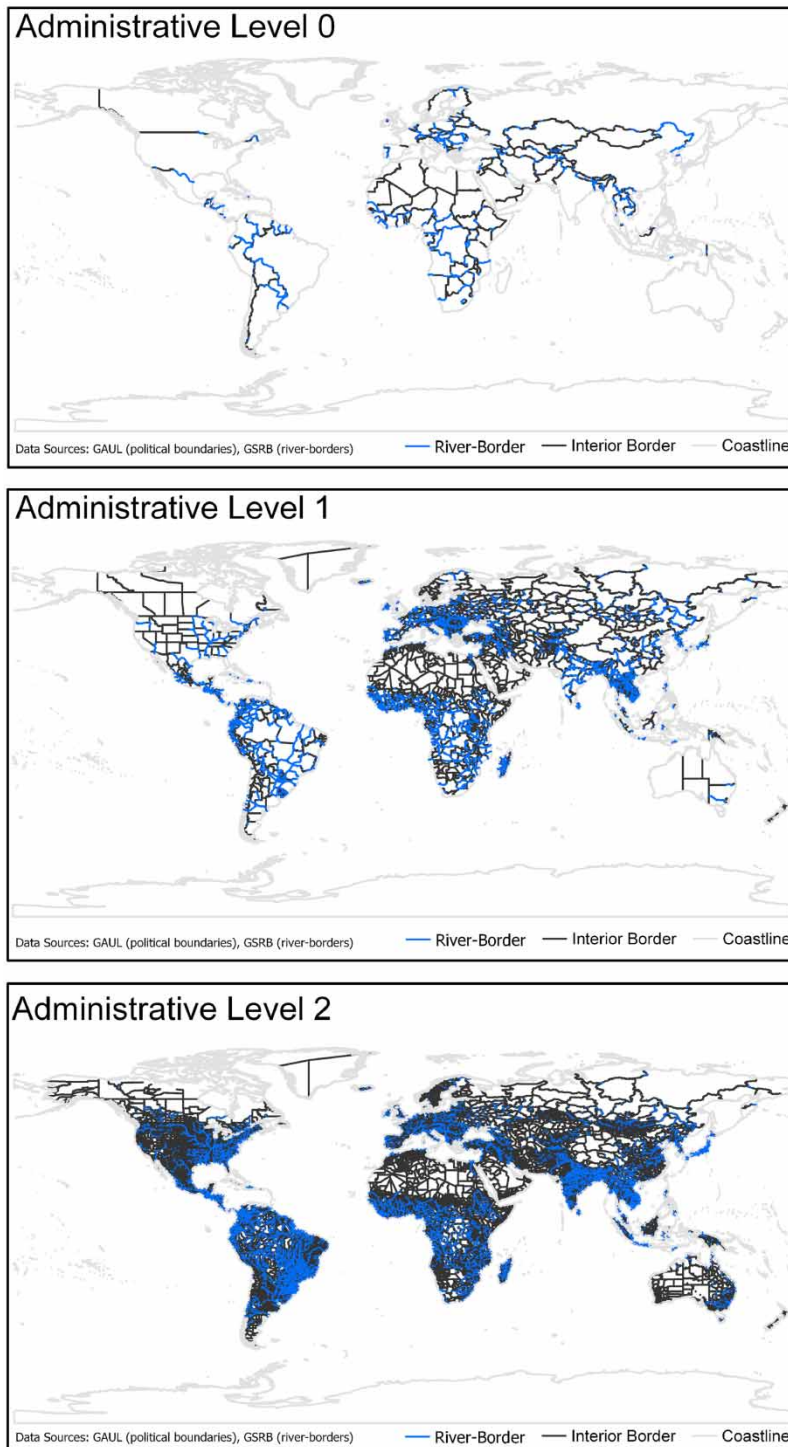


Fig. 5. Global interior (i.e. non-coastal) political borders and river-borders for national (Level 0), state/province (Level 1), and county/local (Level 2) administrative levels. Note the high density of river-borders at finer administrative scales.

Table 2. Total global lengths of all borders, coastlines, interior borders, and river-borders for each administrative level. Lengths are given in kilometers, as well as in percent of all political borders.

Administrative scale	All borders (km)	Coastline borders		Large river-borders		
		Lengths (km)	% of total	Lengths (km)	% of total (including coastlines)	% of total (excluding coastlines)
Level 0 (national)	1,862,034	1,610,230	86	58,588	3	23
Level 1 (state/province)	2,807,933	1,610,230	57	199,922	7	17
Level 2 (county/local)	5,395,609	1,610,230	30	459,459	9	12

river-borders account for approximately 23% of all interior national borders, 17% of all interior state/province-level borders, and 12% of all county/local borders worldwide (Supplementary Material, Appendix A). If the Level 1 and Level 2 analyses are restricted to only those administrative units that actually contain large rivers, the percentages rise to 20% of state/province dyads and to 22% of county/local dyads, respectively.

The use of large rivers as political borders is most widespread in South America, where these natural features comprise 43% of interior country-level boundaries. This finding is consistent with Donaldson (2009) who reports 43%. Barring Australia (which contains no interior national river-borders), we find Asia has the shortest cumulative length of interior national river-borders compared to its other types of borders, with approximately 16% of interior borders coinciding with rivers (consistent with 18% reported by Donaldson (2009)). For Africa, Europe, and North America, the corresponding GSRB estimates of interior national river-borders are 23%, 21%, and 28%, respectively (Figure 6(a)), slightly less

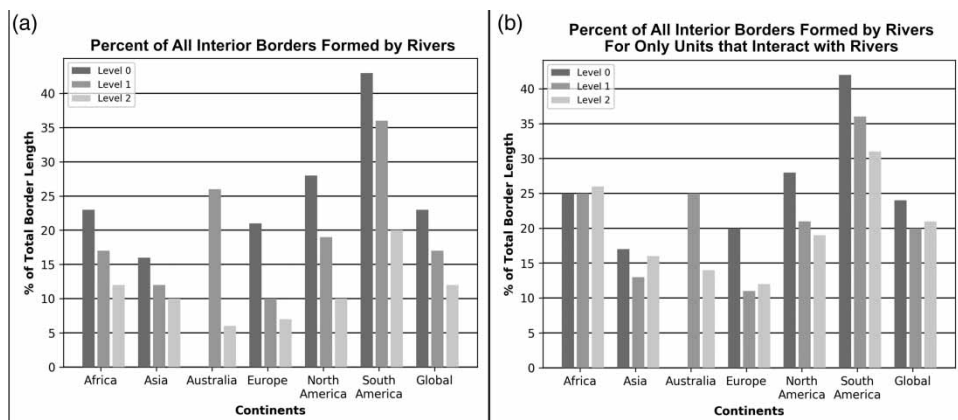


Fig. 6. Percentages of interior (i.e. non-coastline) borders formed by rivers at the national (Level 0), state/province (Level 1), and county/local (Level 2) political-administrative scales. Panel (a) shows percentages including all political units at each level. Panel (b) shows percentages of interior borders formed by large rivers when only those administrative units containing large rivers are considered. Alongside national borders, large rivers are commonly used to define state/province and county/local borders globally. In both panels, South America stands out as a heavy user of rivers for political borders across all administrative scales. Note a slight increase in the values between Panel (a) and Panel (b), particularly at the Level 2 (county/local) scale.

than the corresponding estimates of 30%, 23%, and 32% reported for higher resolution IRBD data (Donaldson, 2009).

At smaller administrative scales, the influence of rivers on political border formation is somewhat less pronounced (in relative terms) than at the national scale (Figure 6). Percentages of interior borders formed by rivers for Level 1 (state/province) administrative units generally range from 10% to 19% with the exception of Australia and South America, where 26% and 36% of interior Level 1 administrative boundaries coincide with rivers, respectively. For Level 2 (county/local) administrative units, the percentage of interior borders coinciding with rivers generally ranges from 6% to 12% with the exception of South America, where 20% of interior, Level 2 administrative boundaries coincide with rivers. If units lacking large rivers (which, therefore, have no opportunity to use them) are excluded from the analysis, the prevalence of river-borders at smaller political scales increases to 12–37% for Level 1 administrative units and 13–32% for Level 2 administrative units (Figure 6(b)). Note that considering only those political units with an opportunity to interact with large rivers yields the greatest increase at the county/local-level (level 2), since those units are far smaller than Level 0 or 1 units, and as such far fewer of them have the opportunity to contain a large river. However, Level 2 units are also far more abundant than Level 0 or 1 units, leading to numerous riparian border states at that level. In total, we identify 141 Level 0, 1,907 Level 1, and 14,128 Level 2 administrative units using large rivers to form political boundaries (Table 3).

Discussion and conclusion

The initial GSRB analysis presented here quantifies the role of large rivers on political border formation across a spectrum of governance scales. In relative terms, the usage of rivers for political borders at subnational scales is generally less but approaches their usage at national scales, especially when limited to administrative units having the actual opportunity to interact with a large river (Figure 7). In absolute terms, of course, the use of rivers for political borders at subnational scales is far higher (1,907 states/provinces and 14,128 counties/local administrative units use rivers as borders, compared to just 141 countries). This, in turn, leads to large numbers of subnational dyads (2,350 and 14,808 for administrative levels 1 and 2, respectively) (Table 3). As such, subnational as well as national partnerships are critical for whole-basin river management, as rivers are commonly shared at fine administrative scales. While not specifically presented here, the spatially explicit nature of GSRB also enables ready identification and quantification of urban rivers (Smith, 2020). The rich

Table 3. Global total numbers of administrative units, riparian administrative units, riparian units having a river-border; and global total numbers of contiguous dyads, riparian contiguous dyads, and riparian contiguous dyads having a river-border. Total counts are derived from GAUL, while the presence of a river and river-border are determined from hybrid GRWL + /WDBII dataset and GSRB, respectively.

Administrative level	Number of administrative units			Number of contiguous dyads		
	Total	Riparian	Have a river-border	Total	Riparian	Share a river-border
Level 0 (national)	276	162	141	354	311	222
Level 1 (state/province)	3,421	2,254	1,907	7,967	5,462	2,350
Level 2 (county/local)	38,257	17,605	14,128	104,259	39,839	14,808

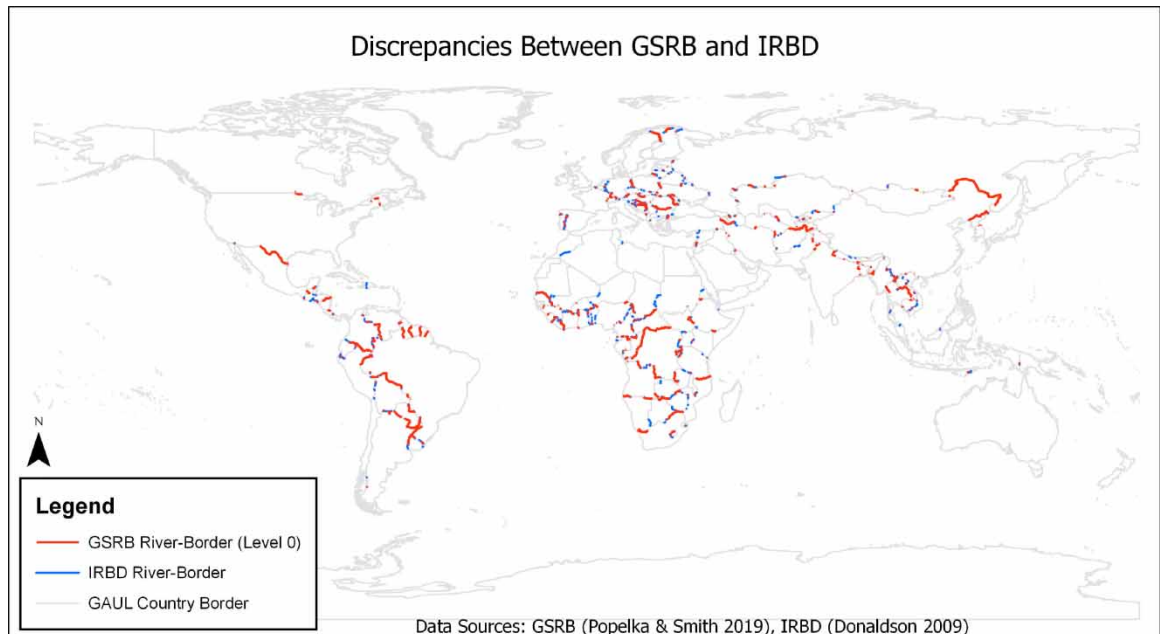


Fig. 7. World map showing discrepancies between national river-borders derived from the GSRB methodology and those obtained from IRBD. Red lines represent national river-borders captured by GSRB, whereas blue lines represent national river-borders captured by IRBD but not GSRB. Note that IRBD resolves numerous river-border segments not included in GSRB, largely due to real-world river-border segments that are formed by smaller rivers than are captured by GRWL ++ and WDBII river platform data. Please refer to the online version of this paper to see this figure in color: <http://dx.doi.org/10.2166/wp.2020.041>.

geospatial and attribute data contained in GSRB will thus support fine-scale studies of potential conflicts, opportunities for cooperation, and urbanization as they pertain to water resource management.

GSRB also provides insights into the historical political organization of peoples across different political scales and geographic regions. A high concentration of state/province and county/local river-borders in the eastern United States, southern Canada, and eastern Australia reflect early settlement patterns and population distributions, with river-borders more common in densely populated areas and straight-line, latitude/longitude borders more common in less populated areas. This observed pattern supports Green (2012), who posits a relationship between population density and the nature of borders. Former colonial territories, in particular, often utilized river-borders in areas of higher population density, whereas straight-lines of latitude and longitude were used in areas with lower population density (Green, 2012). Conversely, colonial powers commonly used large rivers as convenient exploration routes and natural delimiters of territory in poorly charted areas, legacies that persist as subnational U.S. state and county borders along the Mississippi and Ohio Rivers today (Smith, 2020). Our quantification of fewer river-borders in Asia (Table 2) is consistent with less penetration of European colonialism relative to some other parts of the world exhibiting the stronger influence of rivers on present-day border configurations. The marked exception of India, which exhibits a visibly high density of river-borders at subnational scales in the final GSRB map (Figure 5), compared to those within nearby countries, is likely a result of the influence of French and British cartographers in colonial India (Chester, 2000). The high proportion of river-borders to non-river borders across scales in

South America is consistent with the pronounced role that rivers and gaining control over water resources had on state formation in the region (da Silva & Hussein, 2019).

Separately, it has been noted that countries with river-borders are often larger than countries with straight-line borders (Tam, 2004; Green, 2012). However, the examination of our GSRB dataset suggests that Level 1 and Level 2 polities with river-borders are often smaller than those with primarily straight-line borders. Furthermore, while Alesina *et al.* (2011) suggest that ‘squiggly’ lines at subnational scales reflect gerrymandering, our results suggest that a good proportion of such at subnational scales follow natural river courses.

GSRB builds upon an excellent prior river-border dataset (IRBD) to enable the global study of subnational as well as national administrative scales. However, there are limitations to its accuracy. For example, GSRB clearly underestimates river-borders relative to IRBD with regard to both length and quantity (Figure 7). For corresponding segments, GSRB river-border lengths underestimate IRBD lengths by a mean percent error of approximately 24% and median percent error of approximately 10%. This discrepancy is due in main part to the differing spatial resolutions of the datasets used. Although GAUL represents the highest resolution, global, subnational administrative unit data publicly available, at the time of publication, GAUL political boundary lines have a lower resolution than remotely sensed river planform data (note the relatively flat and straight GSRB segment in Figure 3, compared to the underlying satellite imagery and longer and more sinuous IRBD segment). The spatial resolution of the border dataset used directly affects its derivative lengths, as datasets with higher spatial resolution can resolve more and tighter river meanders (yielding a longer total path length from point A to point B), whereas datasets with lower spatial resolution represent river segments using straighter lines and fewer tight bends (yielding a shorter total path length from point A to point B). Donaldson (2009) comments on this issue as well, noting that high-resolution satellite imagery produces more accurate river lengths. Yet, any exact quantification of river-border lengths solely from river planform data is an impossible task, given rivers’ inherent instability, as the spatial location and sinuosity of a watercourse (both of which affect its length) can often change in time, in turn affecting the length and position of the corresponding political boundary or in fact physically departing from it.

Additionally, IRBD resolves boundary segments not resolved in our GSRB methodology (Figure 7). The river datasets we used do not include every river on Earth (nor even every river readily visible in Google Earth), as evidenced by the fact that IRBD contains river-border segments where no rivers appear in the hybrid GRWL + +/WDBII river dataset. There also exist incongruities in the definition of what constitutes a river among the different datasets. Some segments that are considered rivers in the GRWL + +/WDBII dataset and as river-borders in IRBD are considered coastal inlets in GAUL and were, therefore, treated as coastlines in our calculations instead of river-borders. Our quality-assurance procedure of assuming any river-border shorter than 5 km to be spurious further contributes to this underestimation, as it discards some short but true river-border segments that are included in IRBD.

Given these caveats, our lengths and percentages should be treated as highly conservative estimates, rather than precise measurements. However, because GSRB is intended to facilitate broad-scale water management studies, such underestimations are acceptable, as GSRB values report longer borders formed by prominent rivers, rather than streams or dried river beds (which are included in IRBD). In general, large watercourses receive greater interest and motivation for transboundary water resource management agreements than smaller waterways. Future global river-border databases will benefit from the arrival of new, higher resolution, better spatially and temporally co-registered geospatial datasets, and a more parsimonious quality-assurance method. Inclusion of smaller streams (which are not

observable in Landsat-based GRWL + +) in the calculation of river-borders will become possible with the advent of global river mapping using high-resolution CubeSat imagery (e.g. Cooley *et al.*, 2017, 2019), for example. Similarly, higher resolution political border datasets, which can better resolve tight river meanders, will allow for more accurate identification and measurement of river-borders.

While this study did not assess the use of river watershed topographic divides as political borders, we observe that these natural features, too, are commonly used to define political jurisdictions. Therefore, future inclusion of watershed divides, alongside coastlines and river channels, will provide a more comprehensive view of the role of natural physiographic features on political border determination across political scales.

Regardless of these limitations, GSRB represents a novel dataset that should prove useful for trans-boundary river studies at domestic as well as international scales. GSRB can be used as a planning tool to identify all riparian stakeholders at play, including state/province and county/local transboundary neighbors. It establishes a baseline methodology for global river-border mapping using satellite-based surface water products (e.g. Allen & Pavelsky, 2018) which are expected to proliferate following launch of the NASA/CNES/CSA Surface Water and Ocean Topography (SWOT) satellite mission in 2021. Assessing and managing the impacts of hydropower projects, water diversions, land use, and flooding hazards are especially challenging when the rivers at play are also political borders, with competing interests on either side. Identifying subnational, as well as national stakeholders with explicit geospatial mapping, is an important first step toward the development of holistic river management plans that cater to the collective interests of all parties.

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Supplementary material

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