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Characterize river corridor evolution from historical topographic maps

CAN WE CHARACTERIZE RIVER CORRIDOR EVOLUTION AT A CONTINENTAL SCALE FROM HISTORICAL TOPOGRAPHIC MAPS? A FIRST ASSESSMENT FROM THE COMPARISON OF FOUR COUNTRIES

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Abstract

National historical map resources are assessed in four European countries to characterize river corridor features and associated channel changes, as well as identify issues limiting or promoting geomorphic assessment procedures at a continental scale. A geomorphic audit that launches potential data for diagnosis from reach to continental scales, could offer a good resource for biology and ecology managers of river authorities or government agencies, and engineers. The assessment compares the resources available by country in terms of period covered, spatial scale, history and chronology, and representation of the fluvial corridor features. We then applied the Historical Maps Vectorization Toolbox (HMVT), initially developed for vectorising river corridors from French maps, to detect and extract flow channels, unvegetated bars and riparian vegetation patches from historical topographical maps. We found that (i) it is difficult to apply an audit of channel changes to the whole continental scale because map legends differ between countries due to geographic and political specificity; (ii) there exists an opportunity to get assessment information in all countries at reach or national scale where map resources are available; (iii) the highest potential is observed in Switzerland and Belgium

where there is high-quality national map coverage from the 19th century; and (iv) the algorithm HMVT applied to map resources works well with any of the countries and its widespread application is encouraging.

Key words: Historical Maps Vectorization Toolbox (HMVT), channel change, geomorphological audit, diagnosis.

1. Introduction

The geomorphic diagnosis of river channels is becoming a critical step in assessing river health (Montgomery and MacDonald 2002) from an Anthropocene perspective (Brown et al. 2017; Bai et al. 2016). Targeted or guided rehabilitation or conservation based on physical habitat diversity assessment (Piégay et al. 2016) would benefit from better methods and operational characterization tools. Presently, diagnosis of the current state of the river channel health is usually done at a local scale but more and more, is implemented at a regional network scale to improve strategies to restore river corridor features and move from an opportunistic approach (restore reaches where a local demand exists) to a targeted approach (restore the most affected reaches). Tools to characterize river corridor networks exist (e.g., Fluvial Corridor Toolbox – Roux et al. 2015; Alber and Piégay 2017) but historical data are still needed to assess river corridor changes and achieve robust diagnoses (Bizzi et al. 2018, Trimble 2008).

Historical data that can be used to characterise changes in river corridor features are varied (Bizzi et al. 2016; Gurnell et al. 2016). Examples of large scale remote-sensing analyses of river environments, using long profiles and aerial photos, include those that characterise incision/aggradation (Piégay and Peiry 1997), planform changes (Comiti et al. 2011), human pressures (Wishart et al. 2008), or interactions between the two to assess the evolutionary trajectory of river corridor features or the control factors of their changes (Ziliani and Surian 2012; Piégay et al. 2005). With such studies, the most common procedure to detect and characterise river corridor features continues to be the manual interpretation of aerial photo series, usually available on a national scale since the 1940s in many Western countries. The results obtained from this method depend on the fineness and precision of each operator, the characteristics of the image (e.g., colour, scan, shadows, flow level) and the study area characters (channel overhang by vegetation canopy, narrowness of the channel). Operator bias and validation are also an issue (Bishop et al. 2012; Sear et al. 2009). Although it limits the length of river studied due to the effort needed to collect such detailed information, it is still the most reliable method. These methods also require a large volume of data which makes it difficult to implement them on a regional scale. An alternative method to using aerial photographs (i.e. primary data), that may overcome some of these issues, is the use of existing topographic maps (i.e. secondary data). At the regional scale, the use of maps instead of photos is more convenient (Comiti et al. 2011) because the planimetric distortion and the photo interpretation of river corridor features are already handled (Gilvear and Bryant 2016).

Historical maps provide documented records on the condition of different fluvial characteristics with great accuracy, being an important complement to historical aerial photographs. Even though it is also a photointerpretation (i.e. it is simplified), it is usually done by professionals with rules, which confers mapping uniformity. On the other hand, the maps are interpretations of reality, and as such, always present a deformation of it. The veracity with which the rivers are represented and the geometric quality achieved depends on several aspects (Grabowski and Gurnell, 2016). For example, (i) depending on the purpose of the map (e.g. military and defence purposes, land use and agricultural records, civil works), the cartographic quality of the rivers may vary; (ii) the scale of representation also determines the precision of the final result we hope to achieve; (iii) some maps are the result of the enlargements of other maps of different scale, generating a scale of artificial representation.

This paper focuses on the use of maps to assess river corridor features and associated channel changes to feed geomorphic assessment procedures at a continental scale, specifically in Europe. In recent years, European regulations have emerged on restoration and conservation and sustainable management such as the Water Framework Directive 2000/60/EC, Habitats Directive 92/43/EC, Floods Directive 2007/60/EC, or Environmental Quality Standards Directive 2008/105/EC. This new type of river management recognizes that geomorphologic characteristics should be considered in healthy river and land planning. These regulations have led to the proliferation of indexes, many of them geomorphological (e.g., MQI – Rinaldi et al. 2013; IHG – Ollero et al. 2011). Under this context, a systematic extraction of geomorphic information from maps may help to (i) take full advantage of the approaches employing regional databases with historical information, (ii) extend research to long river reaches which cross many countries, (iii) establish connections to the full river in terms of upstream-downstream gradients/connectivity, and (iv) open room for automatization to explore changes on a large (continental) spatial scale.

Our goals are to explore the potential and limits of such a continental scale approach to characterize riverscape changes from cross-comparisons of four European countries (Belgium, France, Spain, and Switzerland) each of which have developed specific national-scale mapping. The aim is to (i) assess the resources available (period covered, spatial scale, history and chronology, topology of the fluvial corridor features); (ii) assess key difficulties arising from the vectorization process to detect and extract features from historical topographical maps, considering the three main components of the fluvial corridor mosaics (flow channels, unvegetated bars and riparian vegetation patches); and (iii) assess the potential use of these resources for fluvial geomorphic audits.

Note we use Supporting Information (SI, onwards) in subsections that are not of general international interest but they are useful nationally, and for specific comments on the research.

2. Methods and data

The workflow was divided into four sequential steps (Figure 1). The first step focused on evaluating the resources available, sending requests to the Administrations (i.e. official map office by country), and data pre-processing. We processed the data using several R packages for data science (e.g. 'dplyr', 'tidyr', 'sp') (RCT 2019; Wickham et al. 2018; Wickham and Henry 2018; Bivand et al. 2013). The final product was a shapefile layer from GIS whose attribute table has six variables (country, scale, sheet number, sheet name, first edition and number of editions). Each field (row) represents a sheet's map. This provided an overview of the resource situation by country. The second step assessed space-time coverage within each country. The third step was the application of the fluvial corridor vectorization algorithm adapted from Dunesme et al. (2018ab), Historical Maps Vectorization Toolbox (onwards HMVT). Dunesme's method requires a scanned and georeferenced topographic map (preferably) as raw data. Its two main work processes are (i) colour layer extraction by automatic sampling and classification in L*ab colour space, and (ii) fluvial corridor objects reconstruction by morphological operations. The algorithm begins by converting the original RGB layer from the input topographical map to L*ab colour space (note that components of a non-perpetual colour space (RGB) are strongly correlated and do not correspond to the human perception of colours, so perceptual colour spaces are more suitable for image processing applied to maps). Unlike the RGB colour space, L*ab is a perceptual space, which provides better results when using supervised classification algorithms. Over this new image, the colours are extracted using a KNN (K Nearest Neighbours) classification to reach the map colour layers. Through the application of topological rules (only the features connected to the main channel are kept) a better final product is achieved to work separately with the flow channel layer, riparian vegetation layer and, if the type of map allows it, unvegetated bar layer. A valley bottom mask was also used to limit the CPU and memory usage during the data extraction process. We applied a buffer function around the valley bottom margin to ensure the entire floodplain was included in the data extraction.

The fourth step assessed HMVT limits through several fluvial geomorphological indexes. The algorithm was applied to four river reaches (one per country) with different geographical features and planimetric changes.

We requested, from Administrations from selected countries, information about analogical topographic maps. We focused on 20K-25K and 50K scales. The original intention was to obtain a broad and continuous study space among six selected countries (Belgium, France, Germany, Italy, Spain, and Switzerland). Table 1 shows how difficult a task it is to access these data at the European scale due to Administrative complexity and specific organisations at country scale.

The resources from the four countries have been represented through eleven maps (Table 2). The features selected for each topographical map were scale, types of legend present in the country history (a key factor in applying the script and calculating of geomorphological change indicators), temporal coverage, number of editions in that time, the year of the first edition, colours employed, and width of the river. The corpus of each country is divided into 2 to 4 types of legend including own individualities in terms of symbol characteristics (colour, shape, generalization) and how these ones represent the fluvial corridor features (e.g. scale or symbol richness (number)).

3. Results

3.1. Genealogy of map resources

The history and chronology of the topographical maps studied in this article have yielded a number of different maps and types of legend by country (Figure 2). SI-C collects a brief history and chronology by country to highlight the most important data for our study.

3.2. Automatic vectorization in action

This section details the results achieved after applying the fluvial corridor vectorization algorithm (HMVT). For this, we have selected four sites (one per country) with different geomorphological features (see SI-D to know more about the geo-characteristics of each site) and changes over the period, and different types of legend, on which to show the possibilities offered by the automatic vectorization in several contexts. In the selection process, we valuated (i) reaches with an intensive corridor evolution to clearly analyse the changes between years, and (ii) an adequate cover time in terms of maximum number of possible maps. Regarding the results, we focused mainly on the algorithm accuracy (what detail geomorphological units are discriminated), which one is different from the map accuracy (what detail of the river was drawn so it is an implicit value of the historical map). We based the algorithm accuracy on the possibility of measuring the channel changes. Manual supervision to check the result reached is necessary. The process is faster with GIS medium knowledge and employing topological rules (e.g. overlaps, gaps, boundaries, etc.).

3.2.1. Case 1. Eau Blanche stream (Belgium) – from sinuous channel to straighter.

HMVT was able to extract 85% of the flow channel from the 1970 map with good quality (Figure 3A). A manual and topological reconstruction was needed in the sections crossed by bridges, administrative boundaries and the latitude-longitude lines. The 1953 and 1870 maps presented more problems. The path of the flow channel was extracted with a width a little higher than the real one due to colour pixel dispersion. Edge artefacts were also present. In both cases, the flow channel was drawn by extracting the middle line of the layer launched by HMVT. Unvegetated bars and riparian vegetation were not present in the reach.

River evolution since 1870 could be very useful as a reference for later restoration projects (meandering river channel and reconnecting remnant meander) (Figure 3A). From 1870 (11.9 km) to 1970 (9.6 km) almost 20% of reach length was lost, going from a sinuosity index of 1.4 to 1.1. From 1870 to 1953 the changes were more specific (4% length reduction).

3.2.2. Case 2. Arve River (France) – reduction of braiding intensity.

It appears that the vectorization process drew the flow channel correctly in most places. Small gaps within the polygon were generated due to the polyline type of this category. Its correction with topological procedures is quick and simple. The unvegetated bars were identified quite accurately when they were surrounded by flow, but showed more complications when part of the perimeter was not adjacent to a flowing channel. However, by means of automatic filling processes, it is possible to complete unvegetated bars that were not identified. A quick visual analysis is also necessary to make sure that the new polygons are not assigned to the riparian vegetation category; this is the category with the most extraction problems because its background is white and it is difficult to set its limits. Manual checks may be necessary in many kilometres of river.

For the Arve river case-study, HMVT helped us to assess the change and read the timeline evolution of the dramatic change of the river corridor (Figure 3B), decade by decade, going from a multi- to single thread. A braiding index (Brice, 1964) of 3.5 was calculated for a sub-reach (~4.5 km) using Type 22 map (1938). In 1981 (Type 72 map) the reach became a straight river (1.04 sinuosity index), with a decrease of ~75% in length of islands and bars.

3.2.3. Case 3. Ebro River (Spain) – meandering channel shifting.

HMVT reconstructed the trajectory of the Ebro River with good quality in four decades following the flow channel (see zoom "d" from Figure 3C). This allowed the delimitation of the space (extent) used by the channel to move. Vectorized polygon quality (e.g. well-defined edges, without roughness, or longitudinal continuity) presents a growing gradient from the oldest year to the most recent. Note that the flow channel for the maps of the 30's (polyline type) only offered good results in certain reaches.

Many mid-channel bars were vectorizable (clearer for 1994 than 1952 and 1979). Riparian vegetation did not have a good distinction, especially because the background colour is the same as other adjacent categories, which makes it difficult to set a boundary. The patch covered other categories beyond the real riparian vegetation so the huge changes suffered from land use change at this site (Horacio et al. 2019) could not be analysed.

The main shift in channel pattern occurred from 1979 to 1994, with a new flow channel being drawn, although the sinuosity index almost did not change between years (1.19 in 1952, 1.20 in 1970, and 1.24 in 1994).

3.2.4. Case 4. Aare River (Switzerland) – from meandering / anabranching to single thread sinuous (meandering).

The flow channel was detected with high accuracy. Internally, artefacts are observed in the form of gaps or cuts due to the great amount of infrastructure that crosses the river (Figure 3D). Its arrangement is simple topologically. The mid-channel unvegetated bars were detected correctly, but not the sidebars, with a low percentage of identification. The riparian vegetation is the category that showed the greatest problems, detecting only small sectors. Its similar symbology with the unvegetated bar category and its white background were notable drawbacks during the vectorization.

River length did not change too much between the four dates analysed. Nevertheless, a big difference in the reduction in the number of islands (90%) or active channel width (86%) was observed from Siegfried map (end 19th century) to 1970 (Figure 3D). The main change occurred between 1910 and 1945 (from Siegfried Map to 1910 these were minor), especially with the construction of several kilometres of canal from 1921 to 1922. From 1945 to 1970 more kilometres of channel were built. Bank erosion was stopped by the infrastructure and the river corridor dynamic clearly reduced.

4. Strengths and limitations for characterising river corridor feature changes from historical maps

4.1. Use considerations

We have organized this section in two parts to highlight the main setbacks from the map resource assessment and automatic vectorisation tests. A summary is proposed in Table 3. Map history and legends are then commented through SI-E.

4.1.1. Space-time coverage

Thanks to successive technical improvements and national efforts to implement mapping policies, many sheets were revised several times and others were developed through generalization.

After the analysis carried out in this study, we have detected three main issues to consider in terms of space-time coverage.

The first issue is the type of date (Table 2). Date may refer to (i) the map series (time elapsed between the first edition of a map series (e.g. Siegfried map) and the last one, see Figure 4A); (ii) edition (time elapsed between the edition (1st, 2nd, 3rd…) of the first and last sheet to cover the whole country; see Table 2); and (iii) temporal survey (temporal coverage on which the edition is based; see Figure 4A). It is then very difficult to really determine what the real date of the hydrographic and vegetation layers is. As a consequence, it is very difficult to accurately survey river changes using the whole map resource. Only a single period of time based on the two extreme dates available can be considered.

The second issue looks forward at the different cartographic plans in the same country. For example, the Swiss Siegfried map was made at 25K for the northern half of the country and at 50K for the other half (see Figure 4C).

The third issue is related to erroneous or missing metadata in terms of dates, name/number of sheets, symbology characteristics, amongst others (see Table 2). A good example is illustrated by the French case, where the number of editions by legend types can be hard to determine (e.g. the case of the first edition) due to a lack of data documenting this (Table 2). Moreover, the number of editions also varies a lot across different sheets (see SI-F to get a deeper explanation about this issue).

This set of problems suggests that it is important to treat the information with caution and analyse each country case in a particular way to interpret the results correctly. A critical approach will be required to achieve a clear understanding of the space–time coverage of the maps. This assessment shows that the coverage of the different national territories is very heterogeneous in terms of dates, scale and number of editions (Table 2 and Figure 4). This makes (i) it a very limited opportunity to make an overall objective censing at European scale over a long time period (~1.5 decades (from 1950s to 1970s) considering the first edition of the historical maps done in twentieth century at 50K; Figure 4A); (ii) it possible that rivers within a single country were mapped at different dates, and with different topographical rules, symbology and scales; Figure 4B shows the diversity of situations that can occur in 90 km of the Ebro River only from two types of map; but (iii) these map resources with similar scale and potentially comparable legend features (flow channel, unvegetated bars and riparian vegetation) are available everywhere (in the countries assessed here) to characterize the river network today, at least for the large to mid-sized systems.

4.1.2. Algorithm computerization

The main unsolved algorithm problems are related to the mixed pixels (cluster with multiple colours) created during the map scanning process. Each scanner can assign a different value based on its parameters, but this value does not correspond to a particular colour so that complicates the reconstruction of features. This problem is smoothed regionally by the amount of data exploited, but may be restrictive for further analysis at the local scale. The flow channels represented by polylines present serious problems in this regard (see Figure 2). The precision of the vectorization of the islands without vegetation of the braided rivers is also considerably reduced as soon as the size of these islands approaches the value of separation between the symbols of the plot that is used to represent the banks.

Other types of potential problems are related to (i) the reconstruction of bridges, toponyms and administrative boundaries; (ii) very poorly preserved maps (e.g. pale colours lead to misclassification); (iii) maps with a high range of colours; and (iv) maps with low green colour to identify vegetation units.

4.2. Historic maps as raw data for a geomorphological audit

The use of historical maps as a secondary-data source in fluvial geomorphology is increasingly widespread (Grabowski and Gurnell, 2016) because the different geomorphological stages of a river result from past and present adjustments of the fluvial system. These cannot be explained by reference only to current conditions, and new methods of analysis and greater emphasis on historical knowledge are necessary (Bishop et al. 2012; James et al. 2012). The anthropic activity of the last 150 years has intensely affected the fluvial processes and forms, especially in Europe because of heavy human pressure (Scorpio et al. 2017; Ortega et al., 2014; Surian et al. 2009; Hooke, 2006). Large rivers were deeply engineered and currently, around less than 10% of total European stream and river length may be relatively free of human impacts (Chandesris et al. 2009).

Nonetheless, the development of tools for automatic extraction of fluvial information from historical maps to quantify changes and reconstruct trajectories has not been so widespread in the field of fluvial geomorphology (low number of references in scientific literature under this topic). There is, on the contrary, a long tradition in the forest, agriculture, land-use, landscape disciplines (Statuto et al., 2016; Fuchs et al. 2015; Tortora et al. 2015; Herrault, 2015; Herrault et al. 2013; Yeo and Huagn, 2013) or geomatics (Dupont et al. 1998; Frischknecht et al. 1998; Mariani et al. 1997). The first initiatives to search for automatic process tools to extract vector or raster information layers have also been taken from these disciplines (e.g. Loran et al. 2018; Petit and Lambin, 2002; Brow 1998). In the fluvial area, the first attempts to work with old maps begin to appear in recent years (Dunesme et al. 2016; Marchese et al., 2017). However, at the moment, historical data is mainly used to validate the results, sometimes at network scale (e.g. Bizzi et al. 2018) and more commonly at reach scale (e.g. Arnaud et al. 2019; David et al. 2016).

The lack of extensive retrospective data is a handicap to establish fluvial diagnoses, which cannot be solved by the most advanced techniques in remote sensing or aerial images (usually since 1940s). In this context, historic maps are linked with the geomorphic changes that can affect the rivers at decadal and reach scale, turning them into a very useful tool for fluvial (geomorphological) audits, which one attempts to structurally relate (under a systemic approach) to the river processes and forms at reach or basin scale (Sear et al. 1995). Regarding geomorphological audits, our analysis of historical maps can provide quantitative information on the geomorphological characteristics at a given moment and show changes (trajectories) over time (Figure 3); it is necessary to understand the trajectory of the rivers to predict their future evolution or estimate the probable morphological response against potential impacts. The extracted information by HMVT can also provide a proxy to evaluate the morphological impacts caused by gravel mining (Figure B), land use changes (Figure 3C), or engineering works on the channel (Figure 3A-D), among others.

The scope of a geomorphologic audit may be limited by the time and resources available for the river / reach (Thorne, 2002), if having to draw upon primary datasets (i.e. photointerpretation) to generate information about river condition. HMVT can produce exploitable data to work at continental, national, regional (basin) or reach scale, and with production times faster than the manual procedures of classical photointerpretation. HMVT execution process (masking >> conversion >> sampling >> classification >> reconstruction >> validation) needs from 2 to 4 minutes per map to run the Ebro River reach (Figure 3C). This means an execution capacity of 1,000 km of river in less than 3 hours.

Figure 5 shows the potentiality of the HMVT in the use of historic maps in the four countries analysed to answer what can be done (replicable in other contexts). We compared five common geomorphological indicators of change over time (other indicators of feature changes can be applied too). There is a quality gradient from the maps of older versions to the most recent ones. Since some legends share several editions spread over several decades, it may happen (e.g., Spanish case) that the results are more optimal for the most recent editions than for the older ones despite using the same type of legend. This is due to the improvement of screen-printing techniques. Likewise, even within the same edition differences can be given by sheet depending on the quality of the base (paper analogic map) or scanned process (Table 3). Country comparisons by indicator are more complicated when the map quality is different.

We have tried to synthesize the use of national topographic maps and associated HMVT strengths answering three questions, *where, for whom, and how?*

Where? The geomorphological framework of a river provides an ideal template to evaluate the interaction of biophysical processes within a basin (Brierley and Fryis, 2005), and how the interactions between fluvial and human systems are given (Piégay et al. 2016). Indeed, study sites can also serve to achieve a better understanding of the "river trajectory" in terms of geomorphological history, which is mirrored by the management policies applied on the basin or reach scale over time. Such data are therefore useful at the continental scale to compare present conditions across countries, at national/regional scale to assess changes and get references, to reach scale to determine trajectories. Note also when we move from continental to reach scale, we increase the volume of data needed and reduce the spatial homogeneity due to the increasing number of types existing at more detailed scales.

For whom? Under this framework, the algorithm applied on a geomorphological audit which launches potential data for diagnosis at reach scale, offers a good resource at the continental (European) scale, and it is valuable to biologists, ecologists, and managers of river authorities or government agencies, and engineers.

Characterize river corridor evolution from historical topographic maps

How? Direct / indirect and quantitative / qualitative information collected from topographic maps and reached by HMVT can markedly help the professionals listed above to (i) integrate the geomorphic diversity as a key factor to determine the amount of habitat availability for biotic interactions and associations; (ii) to better evaluate the intensity of changes which occurred at regional to national scales over a river network, (iii) to design and make decisions about river restoration and conservation projects, from impact appraisal to potential responsiveness understanding; (iv) to improve the understanding of future impacts of engineering works and determine if they are morphologically achievable; and (v) to raise awareness about flood risk and how floods spread.

6. Conclusions

The characteristics of historical topographical maps at national scales, such as period covered, spatial scale, legend topology, and chronology are clearly influenced by the historical and geographical contexts of a country. The countries addressed in this study have served to show the close relationship between national political history and topographic resources.

A clear knowledge of the mapping process and associated legends is then a key factor to assess such resources and determine what is feasible or not for geomorphic auditing. Likewise, as in a photointerpretation process, the verification of the quality of the final result must be monitored manually. Employing topological rules and medium GIS knowledge the process is fast.

Historic maps are potentially a unique source of information to assess river channel changes and their associated controls on a wide range of scales over the Anthropocene era, at least after the 1950s and for some countries for the last 170 years. The applied algorithm (HMVT) is optimal for extracting key geomorphological information when quality and map symbology are adequate. The results are very useful in the framework of a geomorphological audit for the development of prospective approaches, as well as for retrospective understanding. HMVT may be useful for other geomorphologists and for engineers, planners and river managers. Depending on the homogeneity of information available at the scale of interest, national cartographic resources can be useful for exploring the present differences between rivers within a country, at national to continental scales (from 1850s to now in the best cases) to analyse channel changes (flow channels, active channels, even whole natural river corridor including riparian zone), or at reach scale, sometimes in a multi-date perspective to feed geomorphic diagnoses.

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Data Availability Statement (DAS)

Data sharing is not applicable to this article as no new data were created or analysed in this study.

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Table legend list

Table 1. Data requests per country with Administration details and response times. See also SI-A.

Table 2. Characteristics of the topographical maps from Belgium, France, Spain and Switzerland produced analogically. Where: type of legend is an ID for each type of legend present in the country history (e.g. Belgium had four types of legends throughout its history) (see *SI-B1* and Figure 2); temporal survey begins with the first survey and ends with the last one (in France it refers to the data revision); number of editions means the maximum number of possible editions per sheet, even though they vary depending on the sheet; first edition refers to the date for the first publication and the last one; colours refer to the tones used in the development of the map (B-black, BE-beige, BI-bister, BL-blue BR-brown, G-green, GL-green light, GR-grey, O-orange, RO-rose, R-red, SI-sienna, Y-yellow,); river width refers to the threshold between polyline and surface representation (from source for thick lines > 'X' meters for surface) (see also *SI-B2*).

Table 3. Issues to be considered when characterising river corridor feature changes from maps.

Figure legend list

Figure 1. Workflow followed in the survey. Rectangular boxes with sharp corners represent: blue for input, green for output, and red for validation. Boxes with rounded corners represent an applied tool: black for R, black + fill-grey for HMVT (simplified version of the method), and soft orange for the FCT (FluvialCorridor Toolbox) algorithm (Roux et al., 2015).

Figure 2. Types of legend symbols in the topographic maps used. The acronyms A, B, C, D mean a type of legend (see see *SI-B1 and* Table 2), FC (flow channel), UB (unvegetated bar), RV (riparian vegetation). Note on France that: unvegetated bar polygons are not changed in Type C whereas aquatic vegetation polygons changed slightly in Type B and Type C.

Figure 3. First box (from above) (A): Eau Blanche stream (Belgium) with a change from sinuous to straighter stream. Flow channel evolution from 1870 to 1970 using three historic topographical maps (a). Vectorization conflicts when the flow channel is crossed by different elements (e.g. bridges, boundaries, other lines) (b). Zoomed-in section of the

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Figure 4. Decades of the first edition and temporal survey of the first maps series developed at 50K in the 20th century and number of editions by sheet and country (A) (note that the French first edition and number of editions were done under poor quality metadata; see Table 2). Temporal and spatial coverage in 90 km of the Ebro River at 25K and 50K (B). Spatial coverage of the Siegfried map at 25K and 50K (C).

Figure 5. HMVT potentiality based on cross-comparison between types of legends by five feature change indicators. Where FCS (flow channel shifting), ACS (active channel shifting), RVNE (riparian vegetation narrowing / expanding), CS (channel sinuosity –change in–), NoI (number of islands –change in–), FTSY (first temporal survey year; see also Table 2). Letters A, B, C, D mean type of legend by country (see Table 2). Colours refer to the quality estimation of the cross-comparison: green (optimal), blue (low precaution, some extra GIS adjustments could be necessary), black (high precaution, much extra GIS adjust are necessary and the final result might not be accurate), and red (not possible: i. algorithm cannot run over the type of legend, or ii. there is not that type of fluvial corridor component). Note that the quality is an estimation which is not a strict rule and a different situation by sheet could happen.

Table 1

Country	Owner	Data accessibility and restrictions	Response time (consults)	Web-address
Belgium (BEL)	National Geographic Institute	Free access through web	< 1 month	http://www.ngi.be
France (FRA)	National Geographic Institute	Free for research and public missions	< 1 month	http://www.ign.fr
Germany	Each *Länder* is the owner	Variable depending on the *Länder*	< 1 month, 1-3 months	Webs owned by *Länder*
Italy	Italian Military Geographic Institute	Unknown	Without response	https://www.igmi.org
	Central Geographic Institute	Unknown	Without response	http://istitutogeograficocentrale.it
Spain (SPA)	National Geographic Institute	Free for non-commercial use	< 1 month	http://www.ign.es
	Geographical Center of the Army	Symbolic fee	> 3 months	http://www.ejercitodelaire.mde.es (CECAF)
Switzerland (SWI)	Federal Office of Topography swisstopo	Free access through web	< 1 month	https://www.swisstopo.admin.ch

Table 2

Country	Map	Scale	Type of legend	Temporal survey	Number of editions	First edition	Colours	River width[a]
BEL	Carte du dépôt de la Guerre	20K	A	1860-1878	1	1865-1880	R, RO, G, GL, BE, B	N.D.
	Type Rapide M735	50K	B	1901-1962	2	1952-1964	R, B, G, BL	> 50 m
	Basic analogic topographic map	25K	C, D	1947-1989	3	1952-1969	B, GR, BI, BL, G, R	>16 m
	Basic analogic General Staff Map M736	50K	D	1962-1986[b]	3	1955-1991	R, B, G, BL	> 15 m
FRA	Topographic Map Type 22	20K, 50K	A	1922-1952	N.D.	N.D.	B, BL, BI, O	> 10 m[c]
	Topographic Map Type 52-64[d]	25K, 50K	B	1950-1975	N.D.	N.D.	B, BL, BI, O	> 6 m
	Topographic Map Type 72	25K, 50K	C	1970-1995	N.D.	N.D.	B, BL, BI, O	> 7.5 m
SPA	National Topographic Map	50K	A, B	~1870-1968	2-11	1875-1968	B, R, BL, G, SI	Variable value
	National Topographic Map	25K	B	~1971-2002	1-6	1975-2002	B, R, BL, G, SI	Variable value
SWI	Siegfried Map	25k	A	1870-1926	9	1870-1922	B, BR, BL	Not listed
	Siegfried Map	50k	A	1870-1926	9	1870-1926	BL, BR, B	Not listed
	National Map	25K	B	1938-mid-1950s	6-year updating[e]	1952-1979	G, BL, Y, B, GR, BR	Not listed
	National Map	50K	B	1938-mid-1950s	6-year updating[e]	1938-1963	G, BL, Y, B, GR, BR	Not listed

[a] Width threshold between polyline and surface representation (from source for thick lines > 'X' meters for surface)

[b] M736 map is based on the M834 map and specific surveying is added. Basic map M834 (25K) was surveyed before M834 map was written.

[c] This type has two thresholds: 5 m and 10 m.

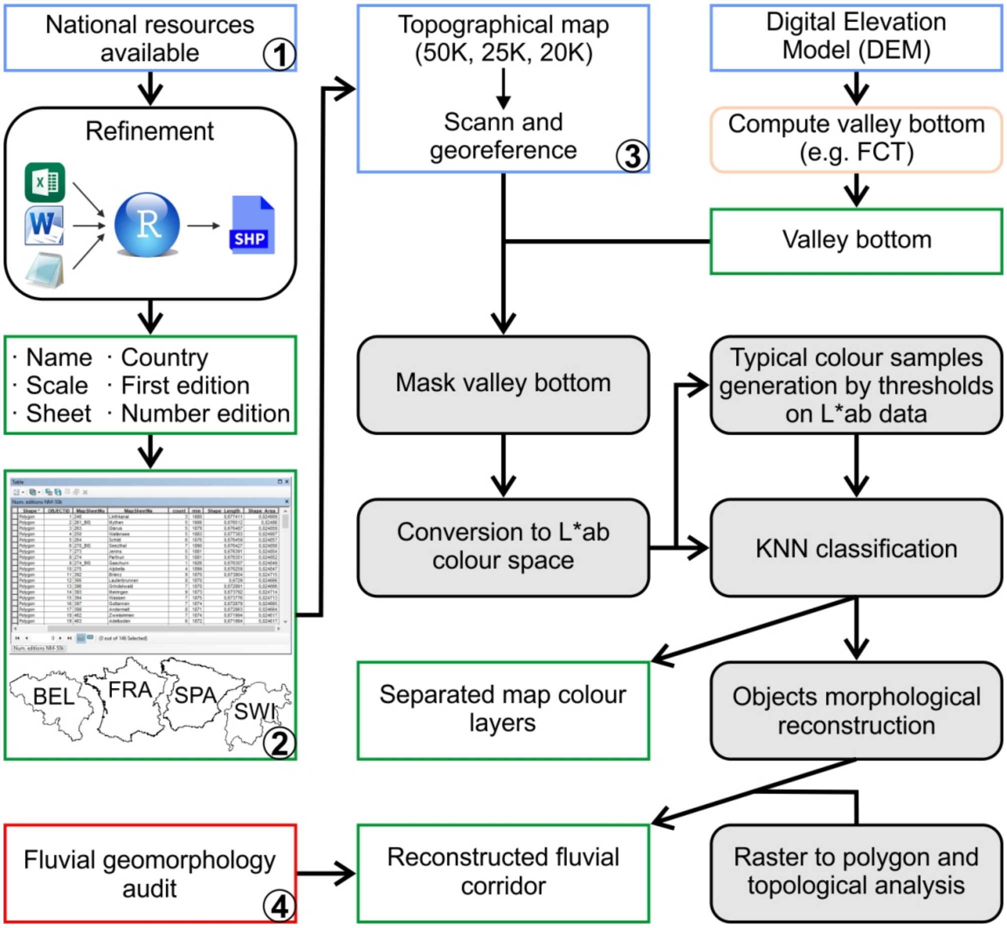
[d] 64 is a simplification of 52 (not important for the hydrography)

[e] 6-year updating cycle in 1968 (there are exceptions too); there are 26 editions of the legends for the National Map

N.D. = no data; metadata not good documented; no found

Table 3

Map history and legends		Space-time coverage		Algorithm computerization	
Specific choices according to country contexts	- Purpose type of map	Type of date (by)	- Map series	Scanning process	- Mixed pixels
	- Temporal coverage		- Edition		· Analogic map quality
	- Symbology		- Temporal survey		· Scan machine quality
Legend	- Flow channel	Cartographic plans	- Different plans in a country	Map colours	- High range of colours
	· Type of symbol	Metadata	- Erroneous (dates, symbology, sheets…)		- Low green colour
	· River width threshold		- Missing (dates, symbology, sheets…)	Reconstruction units	- Bridges
	- Unvegetated bar	Changes	- Cartographic rules		- Toponyms
	· Without explicit category (legend)		- Normative		- Administrative boundaries
	· Nearby categories (part of)				
	· White background				
	- Riparian vegetation				
	· Without explicit category (legend)				
	· Nearby categories (part of)				
	· White background				



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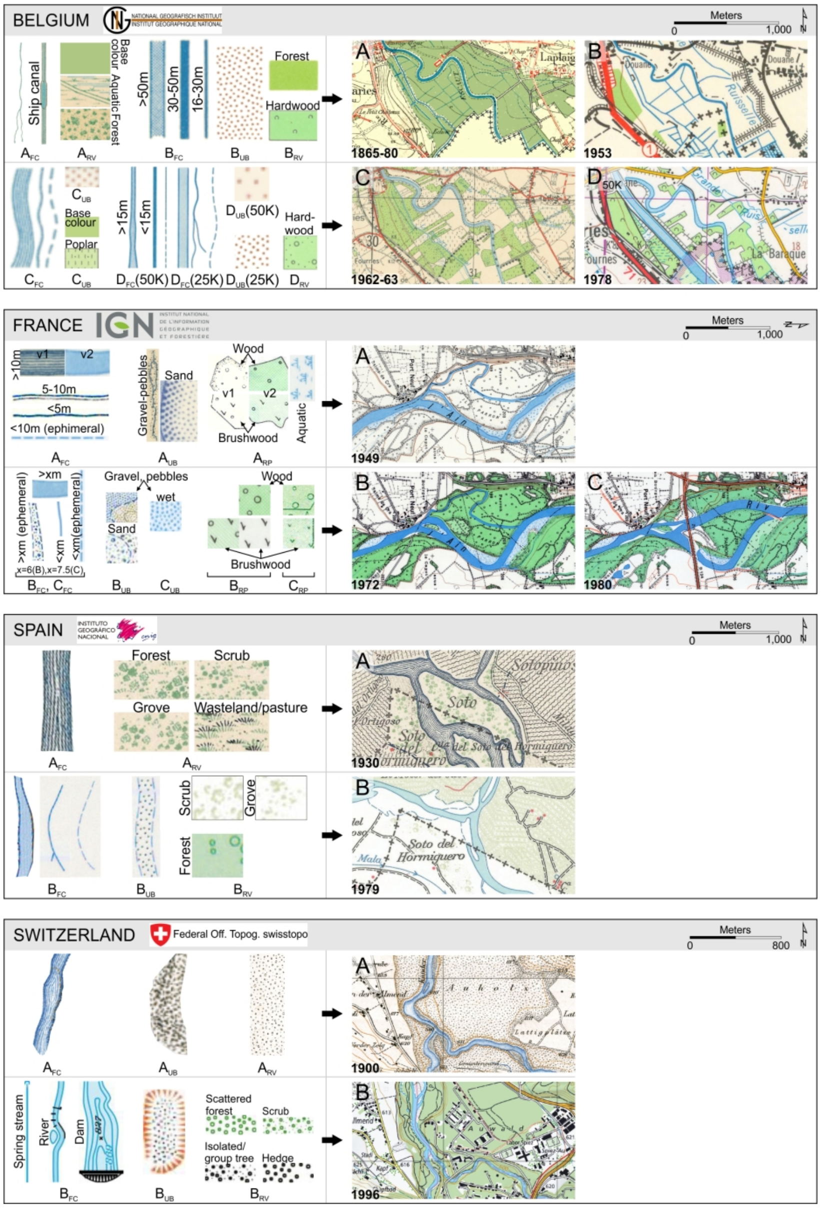

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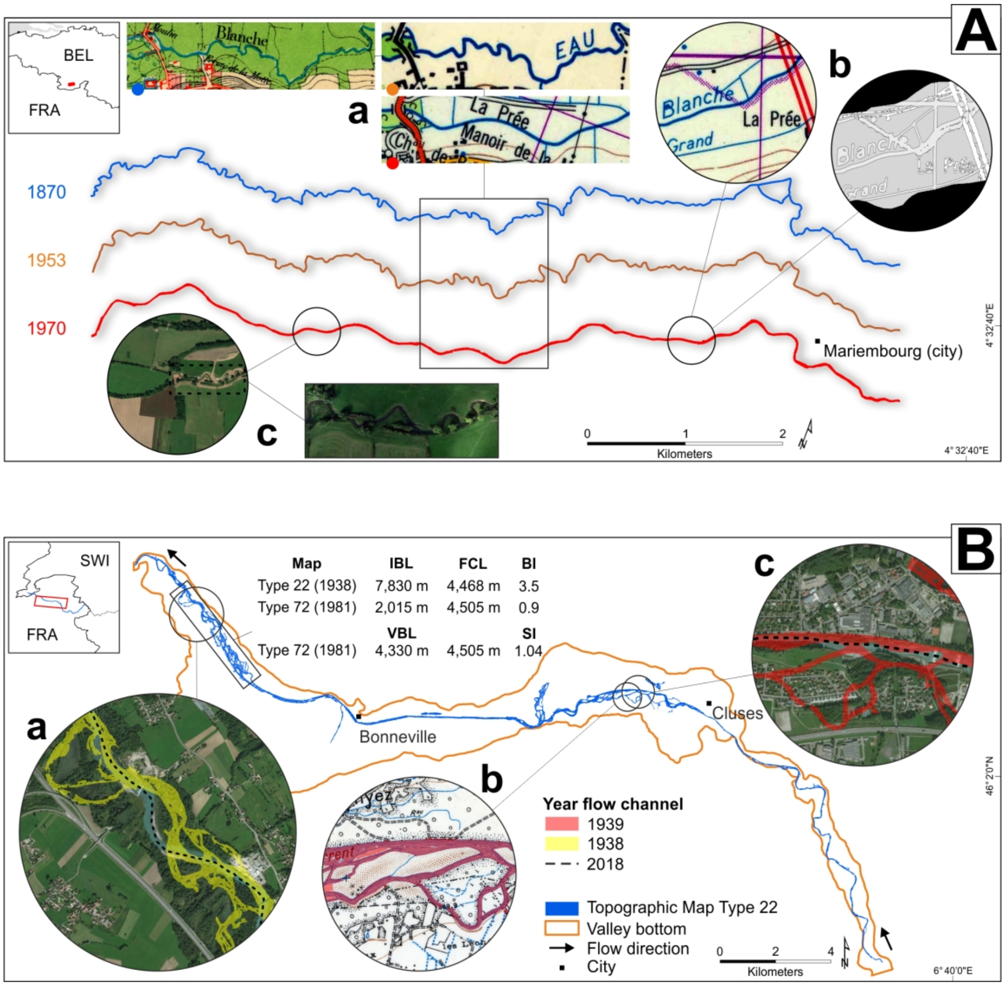
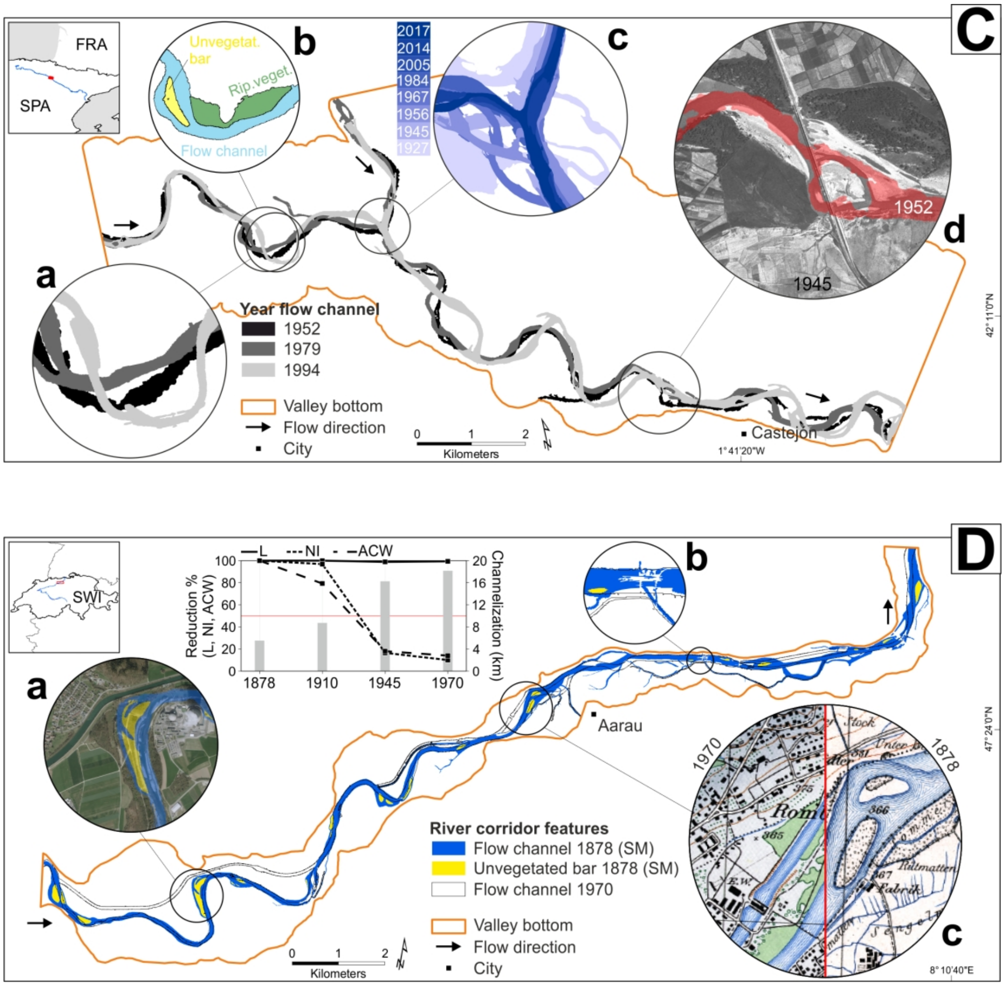


Figure 3a 3b. First box (from above) (A): Eau Blanche stream (Belgium) with a change from sinuous to straighter stream. Flow channel evolution from 1870 to 1970 using three historic topographical maps (a). Vectorization conflicts when the flow channel is crossed by different elements (e.g. bridges, boundaries, other lines) (b). Zoomed-in section of the studied reach and restoration works during and after in relation to Walphy - LIFE project (WLp, 2019) (c). Second box (B): Arve River (France) with a change from a braided to narrow single-bed river. Example of the dramatic geomorphological change occurred from 1938/39 to 2018, where BI (braiding index), SI (sinuosity index), IBL (islands and bar length), FCL (flow channel length), and VBL (valley bottom length) (a). Comparison between historical map (1938/39) and HMVT's layer extracted (b). Anthropic pressure on the floodplain reduced the room for the river (c). Third box (C): Ebro River (Spain) as a channel shifting case study. HMVT in action: several flow channels showing the change in the time-window surveyed (a). Example of river corridor features extracted by HMVT (without topology rules applied) (b). Example of the channel dynamics in the confluence Aragón River with Ebro River from 1927 to 2017 (Horacio et al. 2019) (c). HMVT's layer extracted overlapping the old aerial photo used to make the map (d). Fourth box (D): Aare River (Switzerland) as a change from meandering / anabranching to single thread sinuous (meandering) case study (where L (length) follows the mid-point of the main channel, ACW was calculated as the maximum extent between the banks of the channel polygon vectorized tracing eleven cross-sections along the river and summing all lengths (100%), and SM means Siegfried Map). Aare River channelization and the old trace of the flow channel (1878) (a). Layer artefacts on the flow channel generating by HMVT (b). Channel changes from 1878 (Siegfried Map) to 1970 (c).



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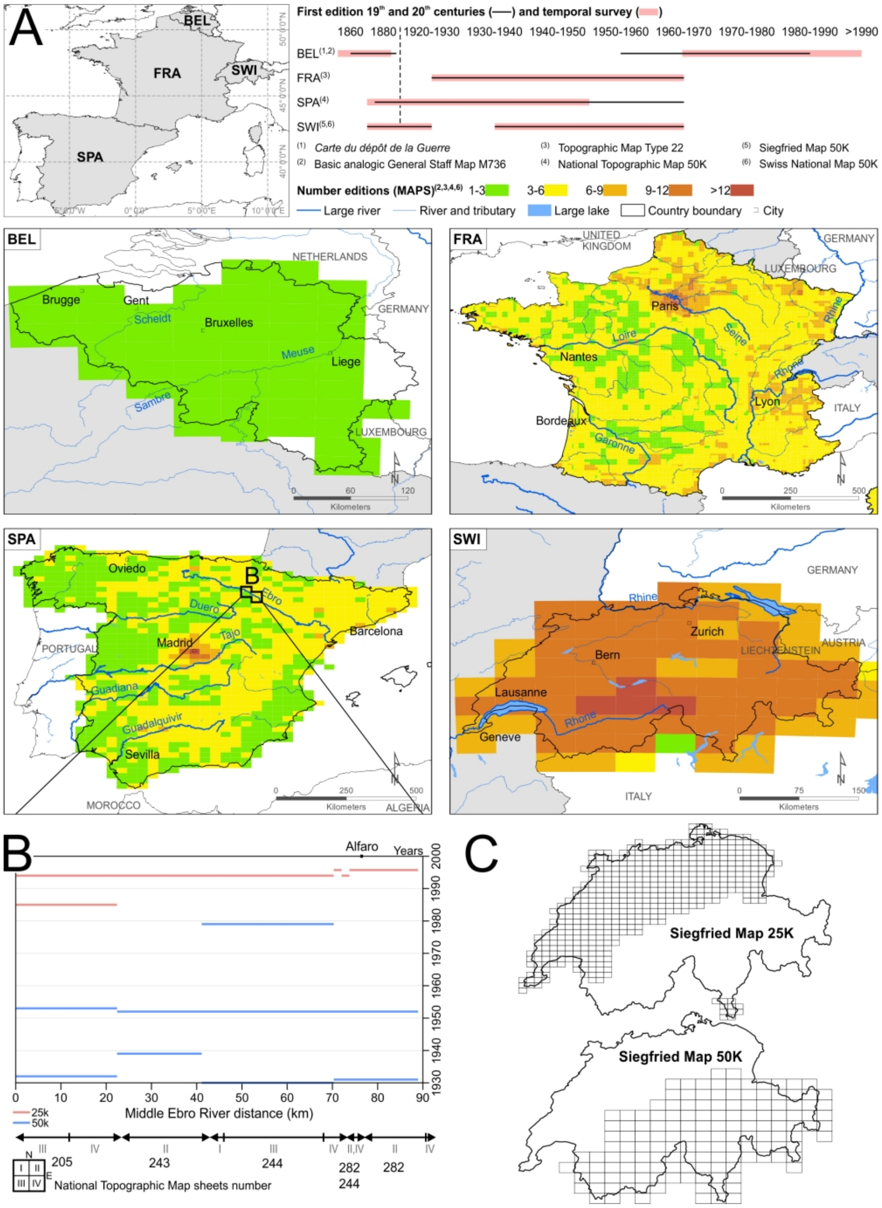

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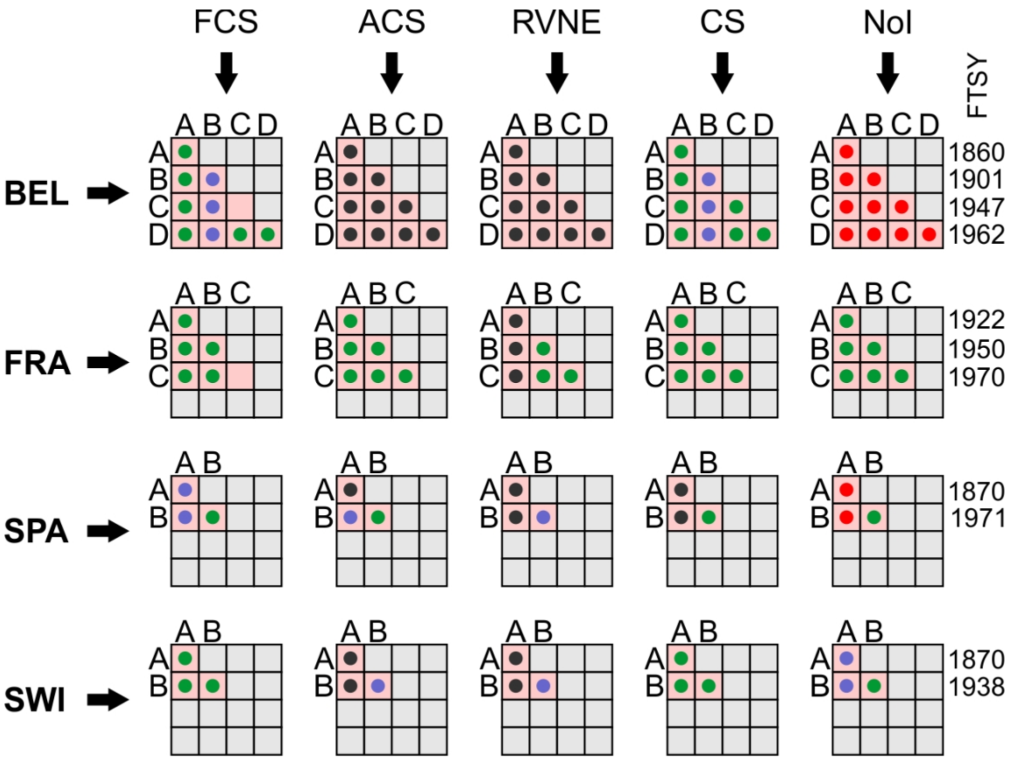

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