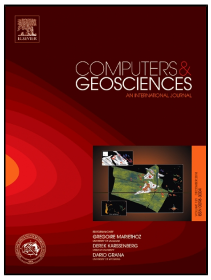
Rivervis

Mao, Feng; Richards, Keith S.; Toland, Mary; Shi, Yichuan; Hannah, David M.; Krause, Stefan

DOI:
10.1016/j.cageo.2018.11.007

Accepted Manuscript



rivervis: a tool for visualising river ecosystems

Feng Mao, Keith S. Richards, Mary Toland, Yichuan Shi, David M. Hannah, Stefan Krause

PII:	S0098-3004(18)30551-X
DOI:	10.1016/j.cageo.2018.11.007
Reference:	CAGEO 4194
To appear in:	*Computers and Geosciences*
Received Date:	08 June 2018
Accepted Date:	10 November 2018

Please cite this article as: Feng Mao, Keith S. Richards, Mary Toland, Yichuan Shi, David M. Hannah, Stefan Krause, rivervis: a tool for visualising river ecosystems, *Computers and Geosciences* (2018), doi: 10.1016/j.cageo.2018.11.007

Computers and Geosciences

`rivervis`: a tool for visualising river ecosystems

Feng Mao[1], Keith S. Richards[2], Mary Toland[3], Yichuan Shi[4], David M. Hannah[1] and Stefan Krause[1]

[1] School of Geography, Earth and Environmental Sciences, University of Birmingham, Birmingham, B15 2TT, UK

[2] Department of Geography, University of Cambridge, Downing Place, Cambridge, CB2 3EN, UK

[3] Northern Ireland Environment Agency, Water Management Unit, 17 Antrim Road, Lisburn, BT28 3AL

[4] UN Environment World Conservation Monitoring Centre, 219 Huntingdon Rd, Cambridge CB3 0DL, UK

Correspondence to: Feng Mao (f.mao@bham.ac.uk)

Authorship statement

FM conceived of the idea presented in the manuscript. FM, YS and KR developed the R package. MT provided the river data used in the manuscript. FM wrote the manuscript in consultation with KR. DH and SK provided feedback and support in revising the manuscript. All authors discussed the results and contributed to the final version of the manuscript.

Abstract

There is a growing need to better understand and communicate multi-dimensional river ecosystem processes and properties at the catchment scale for both scientific research and integrated catchment management. Data visualisation is believed as a very useful approach to support this need. However, there is a lack of visualisation applications tailored for river ecosystems, especially for visualising both river environmental data and their spatial and topological relations. To fill up the gap, this paper introduces an R package `rivervis`, which has been developed as a free, easy-to-use and efficient visualisation solution for river ecosystems. This novel tool is able to visualise riverine data in a compact and comparable way, with retaining the river network topology and reflecting real distance between sites of interest. The `rivervis` package visualises variables according to their measurement types – either quantitative or qualitative/semi-quantitative data. This type-based principle makes the package applicable for a wide range of scenarios with data in forms of index values, condition gradings and categories. By producing topological river network diagrams, the package helps to understand the functioning and interconnections of riverine ecosystem at the catchment scale, especially the longitudinal upstream-downstream and tributary-mainstream connectivity and relationships. It can also be used to study the associations between biological communities, physical conditions and anthropogenic activities. The Ballinderry River Basin in the UK, as a data-rich river basin with a reasonable complex river network, is used to demonstrate the rationale, functions and capabilities of the R-package.

Key-words: freshwater ecosystem, river basin, riverscape, R package, visualisation, up-stream – down-stream relationship

Highlights

- Meet the demand for tailored river visualisation tools for research and management
- Introduce a novel R package to visualise both river data and river network topology
- Help study longitudinal relations and connectivity of rivers at the catchment scale
- Apply a type-based visualisation principle which applies to most data scenarios

1 Introduction

There is an ever growing demand for better understanding of multi-dimensional river environmental data, including upstream-downstream and mainstream-tributary relationships within the river ecosystem (Bunn and Arthington, 2002; Lake et al., 2007; Wohl, 2017). The ecological status of rivers is strongly influenced by upstream conditions, both along the main stream and in the tributaries; and also by the surrounding landforms and land use (Allan, 2004; Bishop et al., 2008; Jackson et al., 2017; Johnson and Host, 2010). Consequently, there has been a long-established history of investigating rivers from a "riverscape" perspective, emphasising environmental gradients, spatial connectivity and complexity (Poole, 2010; Vannote et al., 1980; Ward et al., 2002). Notably, effective river restoration relies on understanding of the upstream catchment context and the downstream effects of upstream degradation and management intervention (Kail et al., 2015; Kondolf et al., 2006). Moreover, newly generated river knowledge and monitoring results are needed to better communicate with a wider audience, to facilitate rational decision-making, and to aid public participation as an increasingly important dimension of river and catchment management (Bunn et al., 2010; Ozerol and Newig, 2008). Recent developments in water management regulations, such as the European Union Water Framework Directive (EU WFD), have also placed a great emphasis on understanding and communicating longitudinal river conditions and properties (Brevé et al., 2014; Quevauviller et al., 2005).

These scientific and operational demands can benefit from visualisation of river ecosystem processes and properties at the catchment scale (Grainger et al., 2016; Keim et al., 2008; Pocock et al., 2016). However, there is a critical lack of adequate tools for the visualisation of riverine data to support such analyses and interpretations. Conventional diagrams, such as long profiles, have been commonly used to present longitudinal elevation and physical gradients of rivers, rather than other types of riverine data including biological, chemical and hydromorphological variables (Rice and Church, 2001). Bar-charts are easy to visualise those quantitative monitoring variables but cannot adequately reflect the spatial structure of the river network or the spatial relationship of sampling sites (see examples in Ran et al., 2018; Spruill et al., 1998). River basin maps with large numbers of sampling sites and variables can appear overly complex and confusing. In addition, we can also generate river basin maps to display both variable values and river network. However, it requires dedicated Geographic Information System (GIS) software, which may be time-consuming to optimise the map presentation or may sometimes incur expensive commercial license fees. Lack of tailored tools means that it can be inefficient to visualise riverine data, or visualisation results may vary among researchers adopting different approaches.

The aim of this paper is to introduce an R-package called `rivervis`, which provides a free, easy-to-use and efficient solution to visualise riverine data in high quality diagrams (Mao et al., 2014). The R software suite has grown substantially in content and users in recent years thanks to its ease of access and flexibility, both for statistical analysis and scientific graphics. The functionality and extensibility of R are supported by an active community with over 10,000 additional packages available on the Comprehensive R Archive Network (CRAN). The `rivervis` package offers new strategies to visualise riverine ecosystems at the catchment scale, which complement or substitute for the above-mentioned conventional diagrams and river basin maps.

2 `rivervis` package strategy and design

2.1 Addressing the challenges of visualising river ecosystems

We identified three main challenges of visualising riverine data at the catchment scale, and offered solutions in the `rivervis` package that transform a river basin map with sampling sites into a `rivervis`-style diagram (Figure 1).

- The first challenge is to visualise data at different sampling sites in a compact and comparable way. For example, parameter values can be plotted next to the sampling sites as bars (Figure 1b). However, this approach makes it difficult to intercompare the bars as they are not aligned to the same baseline, and may overlap each other due to close proximity of sampling sites at different streams.

- The second challenge is to reflect real distance between sites of interest. As discussed above, the longitudinal gradient is one of the essential features to be visualised, but the meandering river channels on the map make the feature inexplicit. To address these two challenges, rivers are visualised as grey rectangular boxes, with the width representing the relative length of rivers and height showing the longitudinal profile of each river (Figure 1c).
- Last but not the least, the third challenge is to visualise river network topology. Many approaches have been invented to visualise topological structures in other fields. For example, the renowned Minard Map and its successor approaches such as flow charts and Sankey diagrams illustrate the topology by visualising the proportional quantity of objects (e.g. people, energy, and water) moving from one location or sector to another (Schmidt, 2008). Other examples include 2-dimentional representation of coronary artery trees for heart disease diagnose (Borkin et al., 2011), genotype data comparison (Fry, 2004), and various ecological networks (Pocock et al., 2016; Raymond and Hosie, 2009). Inspired by these approaches, the package retains the topological structure and relative positions of rivers, and connects the mouth of the tributary with its location on the joining river (Figure 1d, and Figure 1e for optimised layout using less rows). The relative positions of rivers are defined according to the flow direction: following the direction of flow, the left bank of the river and its left bank tributaries are positioned on the left while the right bank of the river and its right bank tributaries on the right.

2.2 Visualisation process and package functions of `rivervis`

The `rivervis` package and several categories of tailored functions were developed to address the above challenges (Figure 2). In order to compactly and comparably visualise riverine data in reflecting real distance and river network topology, the package follows a three-step visualisation process (Figure 2a). Firstly, `rivervis` plots the layout chart of the river network. `RiverLayout()` calculates plotting coordinates for all tributary rivers to be shown on the diagram. Based on the outcome of

`RiverLayout()`, `RiverDraw()` generates the river diagrams with topological structure. The user can also customise the result (e.g. plotting coordinates) of `RiverLayout()` before it is passed to `RiverDraw()`. A wrapper function `RiverMap()` combines these two steps for convenience. Secondly, the package plots the site-based data on the river network using points, broken-lines, bars or blocks according to the types of variables (e.g. quantitative, semi-quantitative and qualitative data). Lastly, `rivervis` adds annotation information on the chart, such as tick marks, the plotting scale and the river flow direction and locations/ reaches of interest.

`RiverLayout()` and `RiverMap()` automatically optimise the layout and calculate the best-fit schematic positions of rivers. To achieve this, the functions firstly sort the tributaries according to the distance between their river mouth and the mouth of the mainstream – downstream tributaries have a higher priority in the process of layout optimisation. The initial rows for rivers are then determined by their relative positions, while each row contains only one river (see Figure 1d). After that, the two functions optimise the layout by reducing the number of rows used in the diagram while maintaining the relative positions of rivers. For example, they move outlying tributaries towards the mainstream where sufficient space is available, i.e, in between the tributaries that are closer to the mainstream, resulting in a more condensed layout (see Figure 1e).

The package is also able to plot qualitative and semi-quantitative variables without showing the topological structure for the situation that river network is not the key information to visualise. `RiverBlockChart()` plots rivers in the form of block charts without the river network structure (Figure 2b). This function automatically and simultaneously plots qualitative/semi-quantitative variables and adds relevant annotations on the block charts by default.

The package is compatible with built-in graphic functions in R and does not rely on third-party visualisation libraries such as `ggplot2` and `lattice` (Sarkar, 2008; Wickham, 2009). For example, the diagram titles and legends can be added by `title()` and `legend()` respectively, while the colour can be specified by the function `palette()`, all of which are provided by default in the built-in graphics library (RC Team, 2013).

2.3 Data management and input format

The package uses mainly two sets of data files (in formats such as CSV) (Figure 2). The first file characterises the river network topological layout with five variables: (1) River name; (2) River length; (3) Parent river, that is the "parent" of a river is the river into which it flows; (4) Relative position, that indicates the river position relative to its parent – whether it is a left bank river, right bank river or the main stream; and (5) Distance, that is between the mouths of each river and the mouth of its parent. The second file provides the site information and the environmental variables to be plotted in the charts and contains four variables: (1) Site name; (2) River name, that denotes the river on which the site is located; (3) The along-the-river distance between the site and the mouth of the river and (4) Qualitative or quantitative variables to be shown on the diagram. It is possible to plot multiple input files in a single chart (see Figure 3). For a simplified diagram displaying qualitative and semi-quantitative variables without topological structures, the configuration file may be omitted (Figure 5).

3 Examples of `rivervis` data visualisations

We use the Ballinderry River Basin in Northern Ireland as an example to show the range of options for data display. It is a relatively small but data-rich river basin, while a variety of biological, physicochemical and hydromorphological variables have been collected and are available along the mainstream and most tributaries (Figure 1). The river basin has a watershed of 450 km^2, and a main stream length of 47 km. The Ballinderry River originates on the southern slope of Sperrin Mountain and joins Lough Neagh on its western shore (BREA, 2010). This Ballinderry Basin is included in the surveillance monitoring of the Northern Ireland Environment Agency (NIEA). The NIEA identified several key pressures affecting the water environment, including flow regulation, diffuse pollution, point-source pollution, morphological changes and invasive alien species (NIEA, 2014, 2008). For illustration purposes, a selected set of rivers, monitoring sites and variables in the Ballinderry River Basin were used for visualisation.

3.1 Visualising river networks

Figure 3 and Figure 4 illustrate the topological structure of the river network, using examples of output from `RiverDraw()` and `RiverMap()`. The figures include a total of 8 rivers: 1 mainstream and 7 tributaries. The rivers are allocated in 6 rows, with the mainstream on the third row from the top. The flow direction for all the rivers is from left to right as annotated in the bottom-right corner of the figures. The river flow defines the relative coordinates for each river. For example, Figure 3 shows a river flowing from left to right on the diagram, so left bank tributaries plot above the main stem. The Lissan and Tulnacross join the Ballinderry mainstream from the left while the Kingsmill, Killymoon Claggan and Kildress join from the right. The Ballymully and Rock are left bank rivers to the Lissan and Killymoon Claggan respectively. Thanks to the topological nature of the diagram, adjacent rivers in nearby rows on the diagram do not necessarily imply a closer spatial relationship in reality. This flexibility helps to optimise the river layout which displays most information with less rows (see Figure 1d and e). The rivers connect only with vertical dashed lines ending with black solid dots. Their lengths in the diagram represents relative lengths and monitoring sites are plotted on their relative positions on rivers, with a scale bar in the bottom-right corner for reference.

3.2 Visualising quantitative variables on river networks

Figure 3 charts the Average Score Per Taxon (ASPT) macro-invertebrate bio-index and ammoniacal nitrogen concentration in spring and autumn in 2009, as well as some sites of interest on the rivers. The ASPT, a widely applied index calculated from sensitivity values of macro-invertebrate families, is used to evaluate organic pollution and nutrient enrichment (Hawkes, 1997). A higher ASPT score implies better water quality. To illustrate the graphic functions of `rivervis`, we used plot functions `RiverBar()` to create a double bar-chart, and `RiverPoint()` for a double line-chart. `RiverTM()` then adds tick marks on the Y-axes – the left one is for the ASPT score and right one is for ammoniacal nitrogen concentration. Sites of interest, such as dams, towns, bridges or other locations or infrastructure on rivers can be marked with `RiverSite()`. Using the mark function, two main towns – Cookstown on the Ballinderry and Maghera on the Ballymully are highlighted as orange squares. The mouth of other tributaries without observation sites are also plotted by `RiverSite()`. The fine control exposed by this function also allows, for example in Figure 3, the direction of the triangles to indicate relative positions of the tributaries.

Figure 3 is an example displaying the relations between biological communities and physical conditions, between upstream and downstream reaches and between tributaries and the mainstream. In Figure 3, high ammoniacal nitrogen values generally coincide with low ASPT scores as expected. The two main towns draw down the water quality and the condition of micro-invertebrate communities in the reaches downstream from them – the reaches in the downstream of the two towns have higher ammoniacal nitrogen values and lower ASPT scores than those in the upstream reaches. In the Killymoon-Claggan River, Site F56 has significantly higher ammoniacal nitrogen values and relatively lower ASPT scores than the upstream Site F60. This pattern suggests a potential pollution source between these two sites. In the further downstream Site F56, the water quality in the Killymoon-Claggan recovers gradually, because of natural recovery processes and also probably a dilution effect by the provision of clean water from the Rock River, represented by Site F69.

3.3 Visualising qualitative/semi-quantitative variables on river networks

Figure 4 shows hydromorphological conditions of the rivers in 2009, which were evaluated according to River Hydromorphological Assessment Technique (RHAT) (NIEA, 2009). The RHAT measures hydromorphological naturalness using eight variables, and each variable is evaluated by a five-level system: High, Good, Moderate, Poor and Bad. In Figure 4, a block-chart is generated by `RiverBlock()`: four selected hydro-morphological quality variables are displayed, these being Channel Vegetation, Channel Flow, Bank Vegetation and Riparian land-use. The last two variables were evaluated for both left and right banks of the rivers. River reaches can be highlighted with different colours to represent different reach characteristics. The Upper Ballinderry Special Area of Conservation (SAC) is highlighted by `RiverReach()`. The Channel Vegetation and Channel Flow have relatively higher grades (Good or High) in the Upper Ballinderry SAC than those of other reaches. However, Bank Vegetation and Riparian Land-use display similar degrees of naturalness to the reaches outside the SAC. The elevation profiles, which are plotted by `RiverPoint()`, suggest that the River Lissan, especially its upper reach, has the highest elevation drop within the river basin. The right tributaries of the Ballinderry River have a comparably smaller channel gradient or river drop than the left tributaries, which imply lower river energy. This may also infer a difference indownstream fining rates (see Rice, 1999) – the grain sizes in the right tributaries decrease slower along the river than in the left tributaries of the Ballinderry River.

3.4 Visualising qualitative/semi-quantitative variables without river networks

Figure 5 provides an example of output from `RiverBlockChart()`, which can be seen as a simplified version of Figure 4. This function is prepared for the application context that the topological river network structure or the relative position of monitoring sites and rivers is not the key information to deliver. In Figure 5, each column represents a monitoring site while each row represents a variable. The monitoring sites are grouped by rivers. The variable value is represented by the colour of the block. For block-charts, regardless of topological structures, it is possible to display more than one value in a line within a column. For example, the lowest two rows of the block-charts (Figure 4 and Figure 5) represent the bank vegetation and riparian land-use condition on both the left and right banks. The block-chart reflects some degree of visual similarity with the mosaic plot (RC Team, 2013), but is implemented independently and tailored for the use of riverine data specifically.

4 Potential applications

The `rivervis` package has been developed to visualise spatial information in river basins, and has a wide range of potential applications. As demonstrated, it can visualise spatial relationships between upstream and downstream reaches, between tributaries and mainstream, or condition change in other dimensions ("riverscape", i.e. Allan, 2004). It can also be used to study the associations between biological communities, physical conditions and anthropogenic activities.

The visualisation process follows one simple principle – variables are visualised according to their measurement types instead of what they represent (see Figure 2). Each variable can be classified into one of the three groups: (1) quantitative data, (2) qualitative data and (3) semi-quantitative data. Quantitative (numerical) data have meaning as a measurement, such as diversity index, species richness, biomass, flow velocity and total nitrogen concentration. This type of data can be visualised in bar-charts or line-charts as shown in Figure 3. Qualitative (categorical) data represent characteristics that fall into categories, such as channel substrate types (boulder, cobble, gravel or sand, etc.), and riparian land-use types (woodland, grassland or urban development, etc.). Semi-quantitative (ordinal) data also fall into categories, but with additional characteristics such a ranking order. For example, percentage cover of aquatic macrophytes (e.g. 9 level ordinal scale, Baattrup-Pedersen et al., 2006; Johnson et al., 2007), and ecological water quality evaluation (e.g. 5 level ordinal scale, European Commission, 2000). Qualitative and semi-quantitative data are suitable for block-charts as shown in Figure 4 and Figure 5.

This type-based visualisation principle can be generalised and applied in many potential scenarios. For aquatic ecological research, `rivervis` can visualise the spatial distribution of species. For example, it helps to examine the River Continuum Concept and display how functional feeding groups change along the river (Vannote, 1980). It also helps to reveal how the longitudinal pattern of substrate and sediment in the mainstream are altered by the input of tributaries, and how this alteration consequently changes the distribution of macro-invertebrate composition and structure in the mainstream (Rice et al., 2001; Stoffel et al., 2013; White et al., 2017).

`rivervis` diagrams showing an environmental gradient can be beneficial and helpful for identifying environmental problems, and support river basin management in various ways. For example, pollution from point sources (e.g. industrial discharges, septic tanks and waste water treatment plants) and from diffuse sources (e.g. agricultural land and road runoff to adjacent river reaches), and incoming streams which may have a distinctive pollution or dilution effect on the main channel can be plotted on topological diagrams in the form of highlighted locations or reaches (see Figure 3 and Figure 4), in conjunction with biological and physicochemical monitoring data (Hensley et al., 2014). This juxtaposition of multiple variables graphically can help to discover relationships among pollution discharge, chemical water quality and aquatic biological status. Rare, endemic, as well as alien species can be plotted to identify their spatial relation with other environmental features. For example, barriers along a water course can be problematic to fish passage (Bednarek, 2001; Rolls et al., 2013). By mapping barriers alongside fish data, inhibiting barriers can be identified. Barriers can be sites of interest plotted by `RiverSite()`, while fish communities can be described by quantitative variables such as richness, abundance or other composition parameters. Visualisation can also be of siltation, which may occur downstream of bank trampling and tilled land (Sidle et al., 2006). The visualisation offered by `rivervis` along a river system can pin-point where the sources and sinks of sediment exist (Anthony and Julian, 1999; Meade, 1982), by adding their locations on the diagrams. After all, management decisions can be well informed based on visualisation or a graphic fluvial audit (Eyquem, 2007).

Furthermore, this type of visualisation has implications for restoration scheme design and monitoring. Being able to present biology, chemistry, hydrology and morphology visually throughout a river system will feed into identifying and designing programmes of measures for the EU WFD. Knowledge on locations of well-maintained ecological status is a pre-requisite for water quality restoration for the WFD (Jackson et al., 2015), and the multi-dimensional circumstances in which "good" status is found can be rapidly retrieved. River typology is an issue in the application of the WFD, and `rivervis` could be used to plot reference river sites for a range of types of river to identify their common attributes. The `rivervis` scheme could be used to assist in assessing planning applications, such as for hydropower schemes where a combined impact may be problematic along a system. For example, the Controlled Activity Regulations (CAR) of the Scottish Environment Protection Agency (SEPA) defines percentages of allowed modification along a river reach (SEPA, 2014), which would readily be well assessed using `rivervis`.

Lastly, we designed the package with the goal that it could be easily extended. As can be seen in the previous example, the types of graphics that associate with a data point or line can be bar charts, line charts and block charts. By design, it is possible to embed additional types of charts that may suit specific use cases not already covered by current plotting functions in `rivervis`. We intend for the package to be a basis for generic riverine visualisation, and envisage significant potential values in re-using the topological structure offered by `RiverDraw()` and `RiverMap()`,enabling easily customisable diagrams as well as wider application.

5 Software availability

The visualisations by the `rivervis` suite offer a simple and accessible basis for summarising ecohydrological data both to enhance interpretation in research, and to support management activities and decision-making. The `rivervis` package has been developed and made available at the CRAN, and can be downloaded from a mirror (http://cran.r-project.org/web/packages/rivervis/index.html). It is also possible to install the package from within R by typing `install.packages("rivervis")`. The package provides a detailed help document with example datasets and scripts (http://cran.r-project.org/web/packages/rivervis/rivervis.pdf).

Acknowledgements

We would like to thank the 'River Basin Governance Research Network' project [ESRC grant reference: RES-810-21-0071], and the Cambridge Philosophical Society for their generous support. We would also like to thank the Northern Ireland Environment Agency for providing the Ballinderry dataset.

References

Allan, J.D., 2004. Landscapes and riverscapes: The influence of land use on stream ecosystems. Annu. Rev. Ecol. Evol. Syst. 35, 257–284. doi:10.1146/annurev.ecolsys.35.120202.110122

Anthony, E.J., Julian, M., 1999. Source-to-sink sediment transfers, environmental engineering and hazard mitigation in the steep Var River catchment, French Riviera, southeastern France. Geomorphology 31, 337–354. doi:10.1016/S0169-555X(99)00088-4

Baattrup-Pedersen, A., Szoszkiewicz, K., Nijboer, R., O'Hare, M., Ferreira, T., 2006. Macrophyte communities in unimpacted European streams: variability in assemblage patterns, abundance and diversity. Hydrobiologia 566, 179–196. doi:10.1007/s10750-006-0096-1

Bednarek, A.T., 2001. Undamming Rivers: A Review of the Ecological Impacts of Dam Removal. Environ. Manage. 27, 803–814. doi:10.1007/s002670010189

Bishop, K., Buffam, I., Erlandsson, M., Fölster, J., Laudon, H., Seibert, J., Temnerud, J., 2008. Aqua Incognita: the unknown headwaters. Hydrol. Process. 22, 1239–1242. doi:10.1002/hyp.7049

Borkin, M.A., Gajos, K.Z., Peters, A., Mitsouras, D., Melchionna, S., Rybicki, F.J., Feldman, C.L., Pfister, H., 2011. Evaluation of artery visualizations for heart disease diagnosis. IEEE Trans. Vis. Comput. Graph. 17, 2479–2488. doi:10.1109/TVCG.2011.192

BREA, 2010. Rivers and Loughs [WWW Document]. Ballinderry Rivers Trust. URL http://www.ballinderryriver.org/index.php/trust-area/rivers-and-loughs (accessed 11.9.18).

Brevé, N.W.P., Buijse, A.D., Kroes, M.J., Wanningen, H., Vriese, F.T., 2014. Supporting decision-making for improving longitudinal connectivity for diadromous and potamodromous fishes in complex catchments. Sci. Total Environ. 496, 206–218. doi:10.1016/j.scitotenv.2014.07.043

Bunn, S.E., Abal, E.G., Smith, M.J., Choy, S.C., Fellows, C.S., Harch, B.D., Kennard, M.J., Sheldon, F., 2010. Integration of science and monitoring of river ecosystem health to guide investments in catchment protection and rehabilitation. Freshw. Biol. 55, 223–240. doi:10.1111/j.1365-2427.2009.02375.x

Bunn, S.E., Arthington, A.H., 2002. Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. Environ. Manage. 30, 492–507. doi:10.1007/s00267-002-2737-0

European Commission, 2000. Directive 200/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy, Official Journal of the European Communities. Official Journal of the European Communities.

Eyquem, J., 2007. Using fluvial geomorphology to inform integrated river basin management. Water Environ. J. 21, 54–60. doi:10.1111/j.1747-6593.2006.00046.x

Fry, B.J., 2004. Computational Information Design. Massachusetts Institute of Technology.

Grainger, S., Mao, F., Buytaert, W., 2016. Environmental data visualisation for non-scientific contexts: Literature review and design framework. Environ. Model. Softw. 85, 299–318.

doi:10.1016/j.envsoft.2016.09.004

Hawkes, H.A., 1997. Origin and development of the biological monitoring working party score system. Water Res. 32, 964–968.

Hensley, R.T., Cohen, M.J., Korhnak, L. V., 2014. Inferring nitrogen removal in large rivers from high-resolution longitudinal profiling. Limnol. Oceanogr. 59, 1152–1170. doi:10.4319/lo.2014.59.4.1152

Jackson, F.L., Hannah, D.M., Fryer, R.J., Millar, C.P., Malcolm, I.A., 2017. Development of spatial regression models for predicting summer river temperatures from landscape characteristics: Implications for land and fisheries management. Hydrol. Process. 31, 1225–1238. doi:10.1002/hyp.11087

Jackson, F.L., Malcolm, I.A., Hannah, D.M., 2015. A novel approach for designing large-scale river temperature monitoring networks. Hydrol. Res. nh2015106. doi:10.2166/nh.2015.106

Johnson, L.B., Host, G.E., 2010. Recent developments in landscape approaches for the study of aquatic ecosystems. J. North Am. Benthol. Soc. 29, 41–66.

Johnson, R.K., Furse, M.T., Hering, D., Sandin, L., 2007. Ecological relationships between stream communities and spatial scale: implications for designing catchment-level monitoring programmes. Freshw. Biol. 52, 939–958. doi:10.1111/j.1365-2427.2006.01692.x

Kail, J., Brabec, K., Poppe, M., Januschke, K., 2015. The effect of river restoration on fish, macroinvertebrates and aquatic macrophytes: A meta-analysis. Ecol. Indic. 58, 311–321. doi:10.1016/j.ecolind.2015.06.011

Keim, D., Andrienko, G., Fekete, J., Görg, C., Kohlhammer, J., Melançon, G., 2008. Visual Analytics: Definition, Process, and Challenges, in: Information Visualization. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 154–175. doi:10.1007/978-3-540-70956-5_7

Kondolf, G.M., Boulton, A.J., O'Daniel, S., Poole, G.C., Rahel, F.J., Stanley, E.H., Wohl, E., Bång, A., Carlstrom, J., Cristoni, C., Huber, H., Koljonen, S., Louhi, P., Nakamura, K., 2006. Process-based ecological river restoration: Visualizing three-dimensional connectivity and dynamic vectors to recover lost linkages. Ecol. Soc. 11. doi:10.5751/ES-01747-110205

Lake, P.S., Bond, N., Reich, P., 2007. Linking ecological theory with stream restoration. Freshw. Biol. 52, 597–615. doi:10.1111/j.1365-2427.2006.01709.x

Mao, F., Shi, Y., Richards, K., 2014. rivervis: River Visualisation Tool. Compr. R Arch. Netw.

Meade, R., 1982. Sources, sinks, and storage of river sediment in the Atlantic drainage of the United States. J. Geol. 90, 235–252.

NIEA, 2014. Neagh Bann: Draft River Basin Management Plan. Lisburn.

NIEA, 2009. River Hydromorphology Assessment Technique (RHAT) training guide (2009).

NIEA, 2008. Neagh Bann: Draft River Basin Management Plan. Lisburn.

Ozerol, G., Newig, J., 2008. Evaluating the success of public participation in water resources management: Five key constituents. Water Policy 10, 423. doi:10.2166/wp.2008.001

Pocock, M.J.O., Evans, D.M., Fontaine, C., Harvey, M., Julliard, R., McLaughlin, Ó., Silvertown, J., Tamaddoni-Nezhad, A., White, P.C.L., Bohan, D.A., 2016. The Visualisation of Ecological Networks, and Their Use as a Tool for Engagement, Advocacy and Management, Advances in Ecological Research. doi:10.1016/bs.aecr.2015.10.006

Poole, G.C., 2010. Stream hydrogeomorphology as a physical science basis for advances in stream ecology. J. North Am. Benthol. Soc. 29, 12–25. doi:10.1899/08-070.1

Quevauviller, P., Balabanis, P., Fragakis, C., Weydert, M., Oliver, M., Kaschl, A., Arnold, G., Kroll, A., Galbiati, L., Zaldivar, J.M., Bidoglio, G., 2005. Science-policy integration needs in support of the implementation of the EU Water Framework Directive. Environ. Sci. Policy 8, 203–211. doi:10.1016/j.envsci.2005.02.003

Ran, L., Tian, M., Fang, N., Wang, S., Lu, X., Yang, X., Cho, F., 2018. Riverine carbon export in the arid-semiarid Wuding River catchment on the Chinese Loess Plateau. Biogeosciences Discuss. 1, 1–23. doi:10.5194/bg-2018-51

Raymond, B., Hosie, G., 2009. Network-based exploration and visualisation of ecological data. Ecol. Modell. 220, 673–683. doi:10.1016/j.ecolmodel.2008.12.011

RC Team, 2013. R: A language and environment for statistical computing. R Found. Stat. Comput.

Rice, S., 1999. The nature and controls on downstream fining within sedimentary links. J. Sediment. Res. 69, 32–39. doi:10.2110/jsr.69.32

Rice, S.P., Church, M., 2001. Longitudinal profiles in simple alluvial systems. Water Resour. Res. 37, 417–426. doi:10.1029/2000WR900266

Rice, S.P., Greenwood, M.T., Joyce, C.B., 2001. Macroinvertebrate community changes at coarse sediment recruitment points along two gravel bed rivers. Water Resour. Res. 37, 2793–2803. doi:10.1029/2000WR000079

Rolls, R.J., Ellison, T., Faggotter, S., Roberts, D.T., 2013. Consequences of connectivity alteration on riverine fish assemblages: potential opportunities to overcome constraints in applying conventional monitoring designs. Aquat. Conserv. Mar. Freshw. Ecosyst. 23, 624–640. doi:10.1002/aqc.2330

Sarkar, D., 2008. Lattice: Multivariate Data Visualization with R. Springer New York, New York.

Schmidt, M., 2008. The Sankey diagram in energy and material flow management: Part I: History. J. Ind. Ecol. 12, 82–94. doi:10.1111/j.1530-9290.2008.00004.x

SEPA, 2014. The Water Environment (Controlled Activities) (Scotland) Regulations 2011.

Sidle, R.C., Ziegler, A.D., Negishi, J.N., Nik, A.R., Siew, R., Turkelboom, F., 2006. Erosion processes in steep terrain—Truths, myths, and uncertainties related to forest management in Southeast Asia. For. Ecol. Manage. 224, 199–225. doi:10.1016/j.foreco.2005.12.019

Spruill, T.B., Harned, D.A., Ruhl, P.M., Eimers, J.L., McMahon, G., Smith, K.E., Galeone, D.R., Woodside, M.D., 1998. Nutrients in Streams and Ground Water, in: Water Quality in the Albemarle-Pamlico Drainage Basin, North Carolina and Virginia, 1992-95. doi:10.3133/cir1157

Stoffel, M., Rice, S., Turowski, J.M., 2013. Process geomorphology and ecosystems: Disturbance regimes and interactions. Geomorphology 202, 1–3. doi:10.1016/j.geomorph.2013.06.018

Vannote, R., Minshall, G.W., Cummins, K.W., Sedell, J.R., Cushing, C.E., 1980. The river continuum concept. Can. J. Fish. Aquat. Sci. 37, 130–137.

Vannote, R.L., 1980. The River Continuum Concept. doi:10.1139/f80-017

Ward, J. V., Tockner, K., Arscott, D.B., Claret, C., 2002. Riverine landscape diversity. Freshw. Biol. 47, 517–539. doi:10.1046/j.1365-2427.2002.00893.x

White, J.C., Hannah, D.M., House, A., Beatson, S.J.V., Martin, A., Wood, P.J., 2017. Macroinvertebrate responses to flow and stream temperature variability across regulated and non-regulated rivers. Ecohydrology 10, 1–21. doi:10.1002/eco.1773

Wickham, H., 2009. ggplot2: elegant graphics for data analysis. Springer New York.

Wohl, E., 2017. Connectivity in rivers. Prog. Phys. Geogr. 41, 345–362. doi:10.1177/0309133317714972

Figures

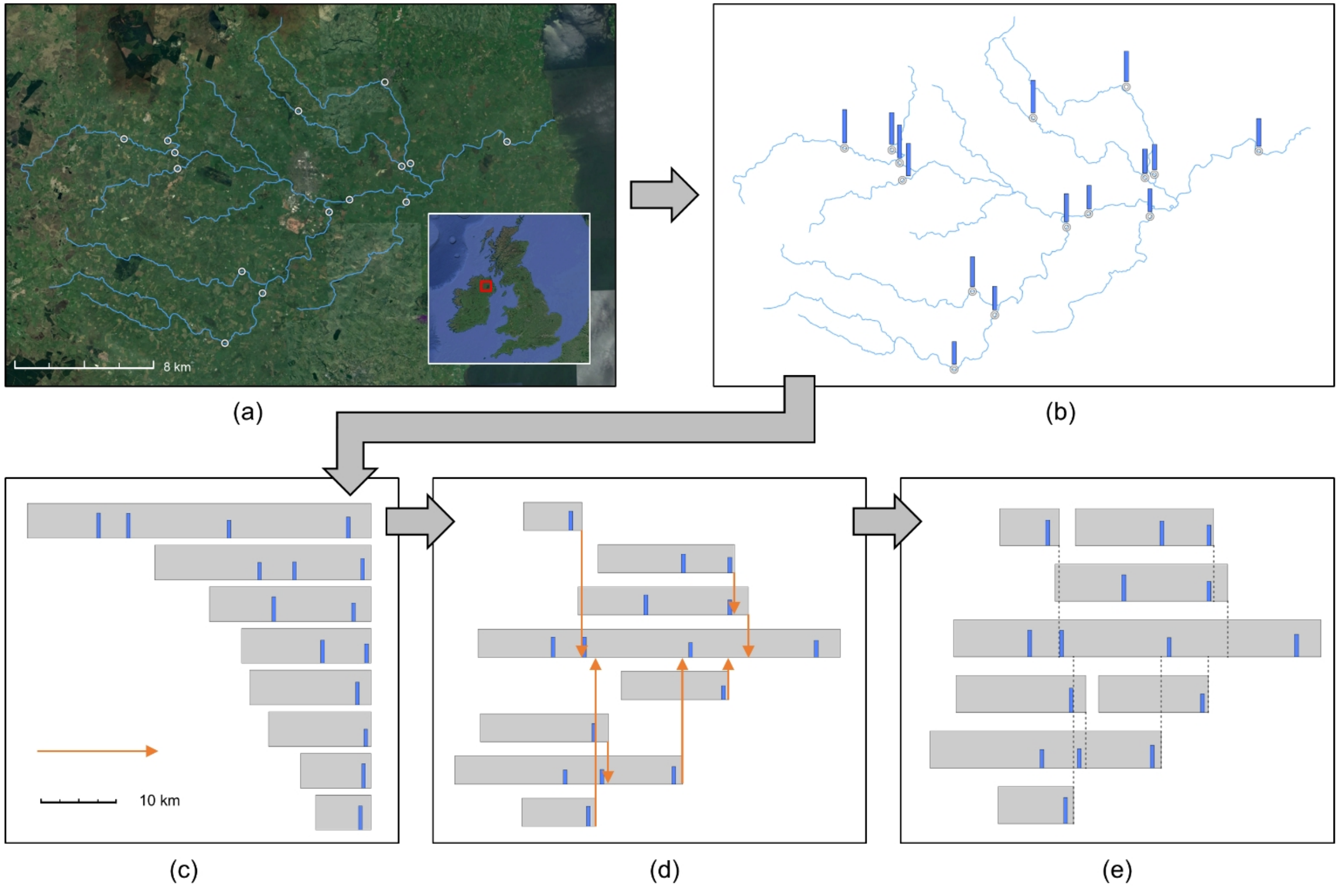


Figure 1. Visualising riverine data with topological structure – from a map to a `rivervis` diagram. (a) A Google Earth map of the Ballinderry River Basin showing main streams and sampling sites (circles). The location of the Ballinderry River Basin is indicated by the red box in the bottom-right thumbnail map. (b) Main Ballinderry streams with bars showing parameter values at each sampling sites. (c) Unconnected Ballinderry streams that have sampling sites. The flow direction is from left to right. The width of each grey box indicates the relative river length. (d) Connected streams showing the topological structure of the river network. It also shows how one stream joins another from left or right bank side. (e) Optimised layout of connected streams. It uses less rows than the previous step.

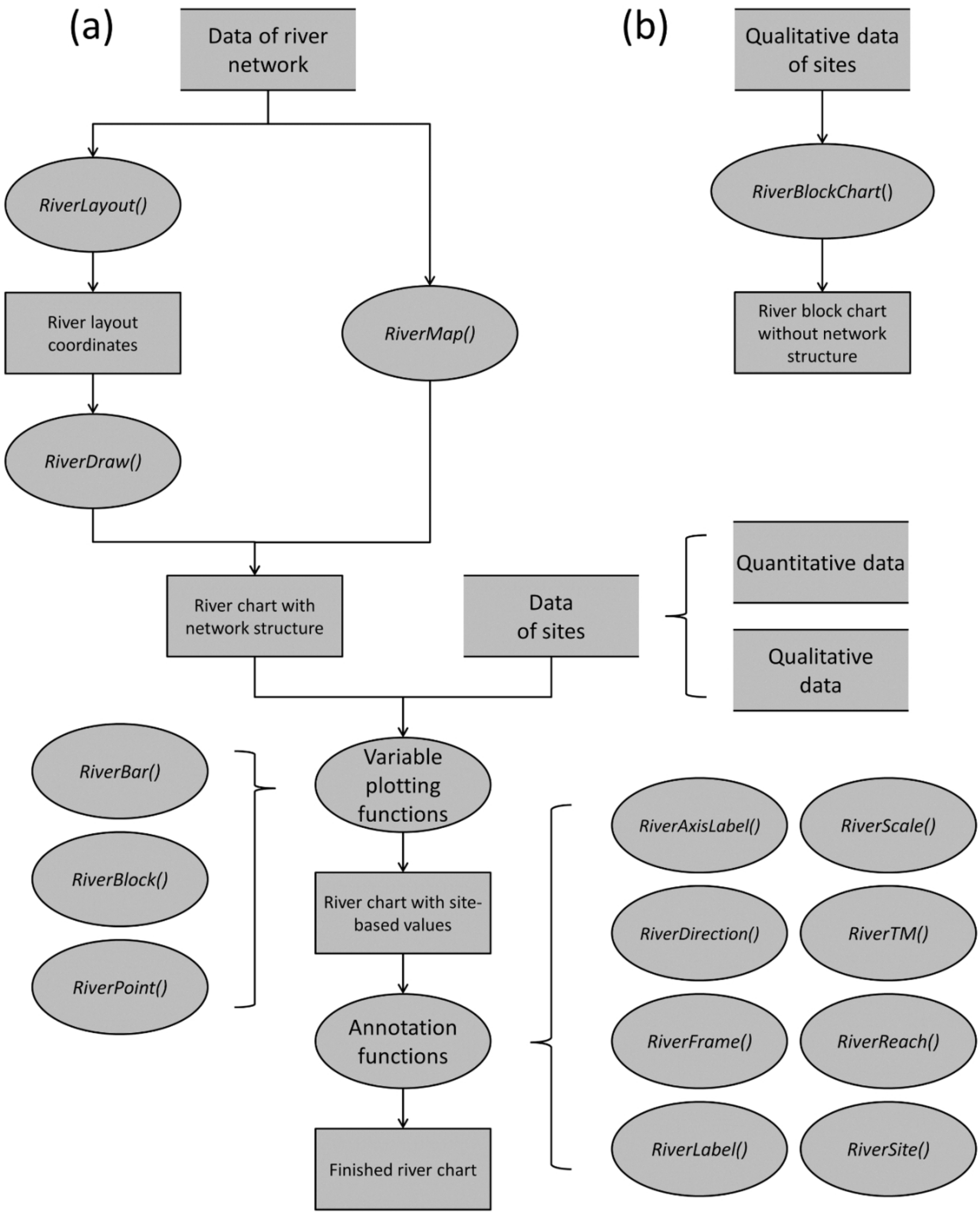
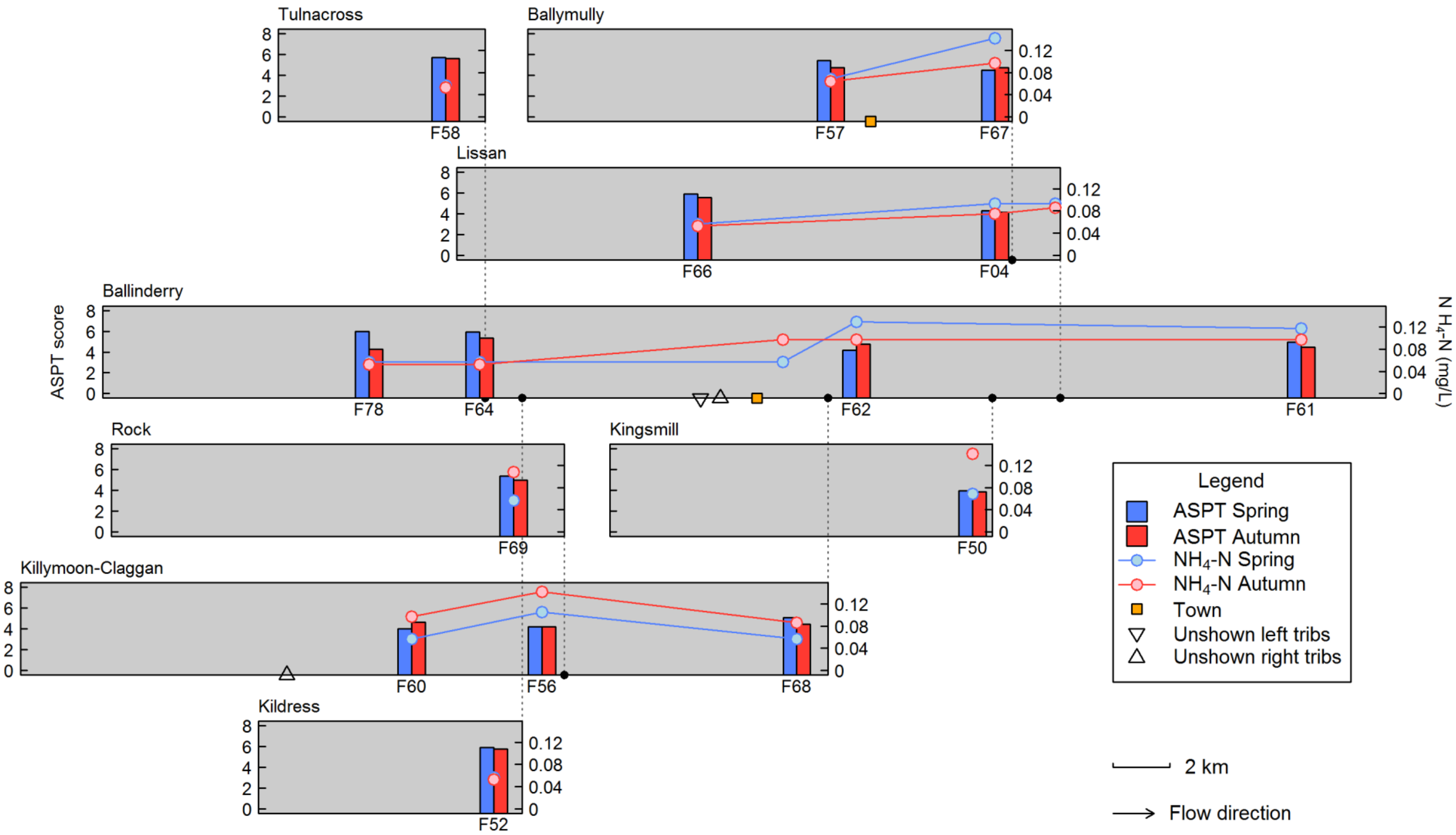


Figure 2. Workflow of the R package `rivervis`. The ellipses denote functions; the boxes with two horizontal lines denote files or data; and the closed boxes denote input or output. (a) Workflow for diagrams with showing river network structure; (b) workflow for diagrams without river network.



486

487 Figure 3. Example diagram produced by `rivervis` for quantitative variables in the Ballinderry River Basin. The black circles with dashed lines denote the location on the rivers where their tributaries join them. The bars denote macro-invertebrate ASPT score while the circles and lines denote ammoniacal nitrogen in spring (blue) and autumn (red) 2009. The orange squares denote the two main towns in the Ballinderry River Basin – Cookstown (Ballinderry) and Maghera (Ballymully). The triangles represent the mouths of some unshown tributaries, with directions implying the relative positions of the tributaries.

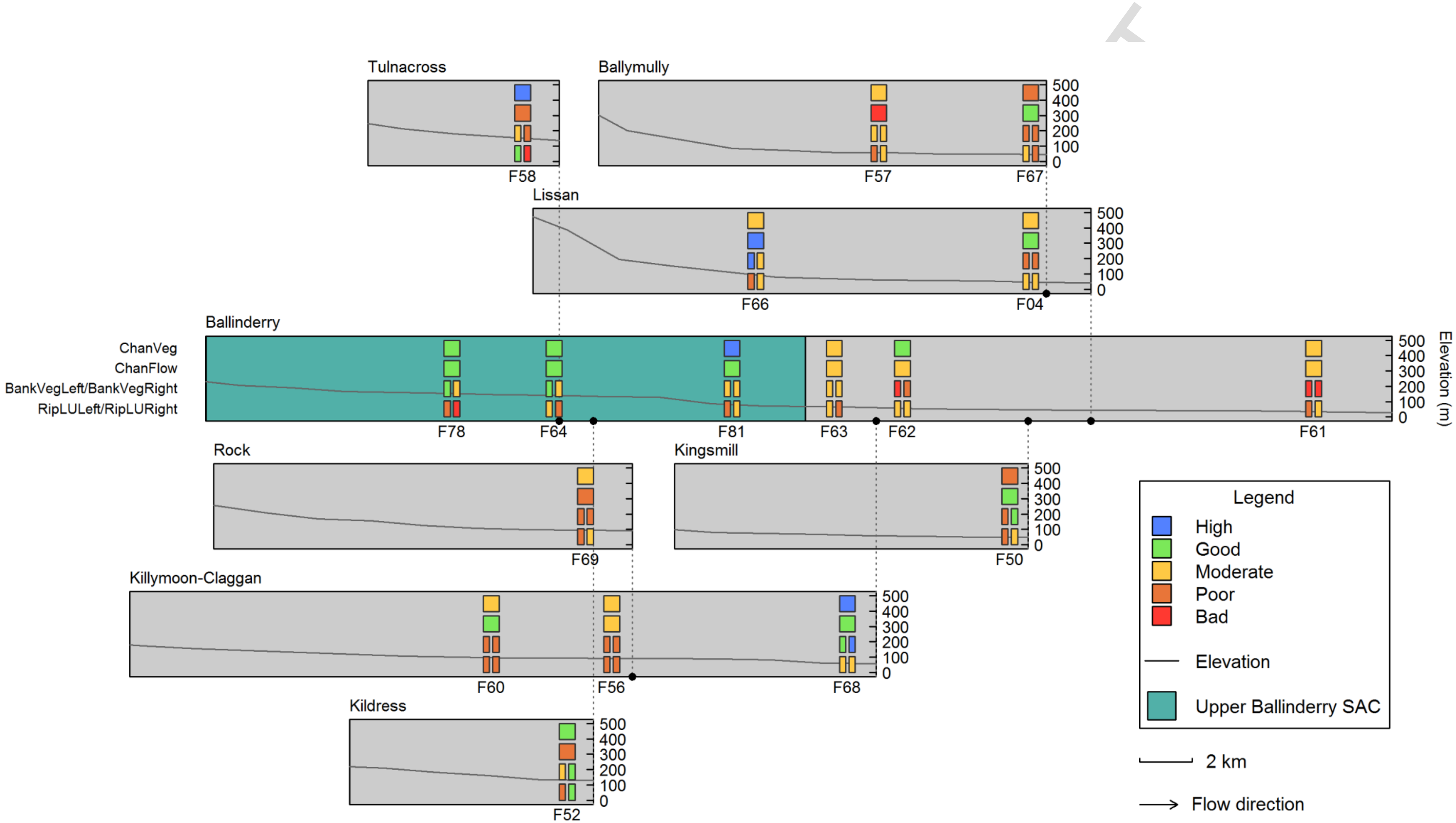


Figure 4. Example diagram produced by `rivervis` for qualitative/semi-quantitative variables in the Ballinderry River Basin. The black circles with dashed lines denote the location on the rivers where their tributaries join them. Four variables, including Channel Vegetation, Channel Flow, Bank Vegetation and Riparian Land-use, while the last two variables are independently assessed on the left and right bank sides. In the diagram, five condition grades (High, Good, Moderate, Poor and Bad) are represented by five colours (Blue, Green, Yellow, Orange and Red) according to the colour scheme used in the European Union Water Framework Directive. In addition, elevation profile and the Upper Ballinderry Special Area of Conservation (SAC) are also shown in the diagram.

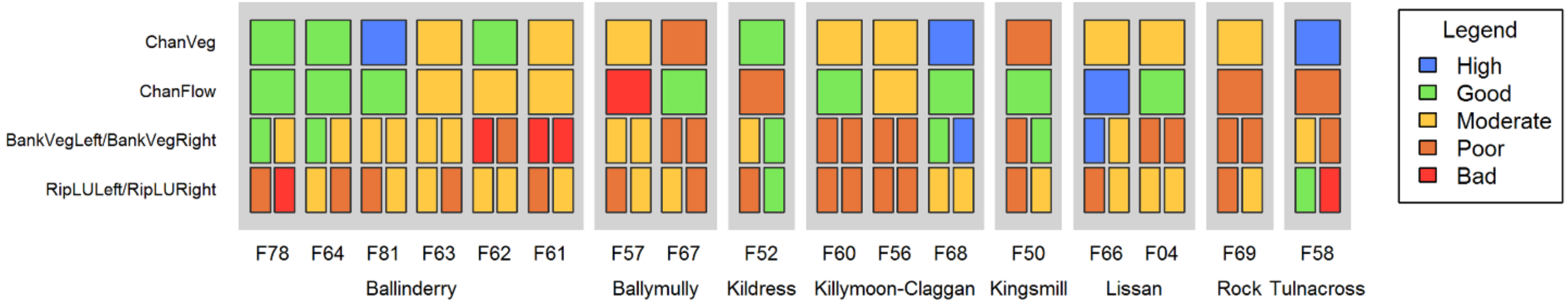


Figure 5. Example diagram without showing topological structure produced by `rivervis` for qualitative/semi-quantitative variables in the Ballinderry River Basin. In the diagram, five condition grades (High, Good, Moderate, Poor and Bad) are represented by five colours (Blue, Green, Yellow, Orange and Red) according to the colour scheme used in the European Union Water Framework Directive.