

Rivervis

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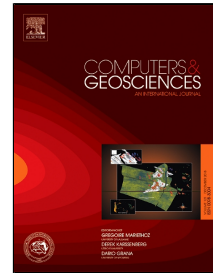
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1 **Computers and Geosciences**

2 **rivervis: a tool for visualising river ecosystems**

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16

17 **Authorship statement**

18 FM conceived of the idea presented in the manuscript. FM, YS and KR developed the R package.

19 MT provided the river data used in the manuscript. FM wrote the manuscript in consultation with KR.

20 DH and SK provided feedback and support in revising the manuscript. All authors discussed the
21 results and contributed to the final version of the manuscript.

22

23

24 **Abstract**

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

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

45

46

47 **Highlights**

- 48
- Meet the demand for tailored river visualisation tools for research and management
- 49
- Introduce a novel R package to visualise both river data and river network topology
- 50
- Help study longitudinal relations and connectivity of rivers at the catchment scale
- 51
- Apply a type-based visualisation principle which applies to most data scenarios
- 52

54 **1 Introduction**

55 There is an ever growing demand for better understanding of multi-dimensional river environmental
56 data, including upstream-downstream and mainstream-tributary relationships within the river
57 ecosystem (Bunn and Arthington, 2002; Lake et al., 2007; Wohl, 2017). The ecological status of rivers
58 is strongly influenced by upstream conditions, both along the main stream and in the tributaries; and
59 also by the surrounding landforms and land use (Allan, 2004; Bishop et al., 2008; Jackson et al., 2017;
60 Johnson and Host, 2010). Consequently, there has been a long-established history of investigating
61 rivers from a “riverscape” perspective, emphasising environmental gradients, spatial connectivity and
62 complexity (Poole, 2010; Vannote et al., 1980; Ward et al., 2002). Notably, effective river restoration
63 relies on understanding of the upstream catchment context and the downstream effects of upstream
64 degradation and management intervention (Kail et al., 2015; Kondolf et al., 2006). Moreover, newly
65 generated river knowledge and monitoring results are needed to better communicate with a wider
66 audience, to facilitate rational decision-making, and to aid public participation as an increasingly
67 important dimension of river and catchment management (Bunn et al., 2010; Ozerol and Newig, 2008).
68 Recent developments in water management regulations, such as the European Union Water
69 Framework Directive (EU WFD), have also placed a great emphasis on understanding and
70 communicating longitudinal river conditions and properties (Brevé et al., 2014; Quevauviller et al.,
71 2005).

72 These scientific and operational demands can benefit from visualisation of river ecosystem processes
73 and properties at the catchment scale (Grainger et al., 2016; Keim et al., 2008; Pocock et al., 2016).
74 However, there is a critical lack of adequate tools for the visualisation of riverine data to support such
75 analyses and interpretations. Conventional diagrams, such as long profiles, have been commonly
76 used to present longitudinal elevation and physical gradients of rivers, rather than other types of
77 riverine data including biological, chemical and hydromorphological variables (Rice and Church,
78 2001). Bar-charts are easy to visualise those quantitative monitoring variables but cannot adequately
79 reflect the spatial structure of the river network or the spatial relationship of sampling sites (see

80 examples in Ran et al., 2018; Spruill et al., 1998). River basin maps with large numbers of sampling
81 sites and variables can appear overly complex and confusing. In addition, we can also generate river
82 basin maps to display both variable values and river network. However, it requires dedicated
83 Geographic Information System (GIS) software, which may be time-consuming to optimise the map
84 presentation or may sometimes incur expensive commercial license fees. Lack of tailored tools means
85 that it can be inefficient to visualise riverine data, or visualisation results may vary among researchers
86 adopting different approaches.

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

95

96 **2 `rivervis` package strategy and design**

97 **2.1 Addressing the challenges of visualising river ecosystems**

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

- 101 • The first challenge is to visualise data at different sampling sites in a compact and comparable
102 way. For example, parameter values can be plotted next to the sampling sites as bars (Figure
103 1b). However, this approach makes it difficult to intercompare the bars as they are not aligned

104 to the same baseline, and may overlap each other due to close proximity of sampling sites at
105 different streams.

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

125 2.2 Visualisation process and package functions of `rivervis`

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

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

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

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

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

157 2.3 Data management and input format

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

169

170 3 Examples of *rivervis* data visualisations

171 We use the Ballinderry River Basin in Northern Ireland as an example to show the range of options
172 for data display. It is a relatively small but data-rich river basin, while a variety of biological,
173 physicochemical and hydromorphological variables have been collected and are available along the
174 mainstream and most tributaries (Figure 1). The river basin has a watershed of 450 km², and a main
175 stream length of 47 km. The Ballinderry River originates on the southern slope of Sperrin Mountain
176 and joins Lough Neagh on its western shore (BREA, 2010). This Ballinderry Basin is included in the
177 surveillance monitoring of the Northern Ireland Environment Agency (NIEA). The NIEA identified
178 several key pressures affecting the water environment, including flow regulation, diffuse pollution,
179 point-source pollution, morphological changes and invasive alien species (NIEA, 2014, 2008). For
180 illustration purposes, a selected set of rivers, monitoring sites and variables in the Ballinderry River
181 Basin were used for visualisation.

182 3.1 Visualising river networks

183 Figure 3 and Figure 4 illustrate the topological structure of the river network, using examples of output
184 from `RiverDraw()` and `RiverMap()`. The figures include a total of 8 rivers: 1 mainstream and 7
185 tributaries. The rivers are allocated in 6 rows, with the mainstream on the third row from the top. The
186 flow direction for all the rivers is from left to right as annotated in the bottom-right corner of the figures.
187 The river flow defines the relative coordinates for each river. For example, Figure 3 shows a river
188 flowing from left to right on the diagram, so left bank tributaries plot above the main stem. The Lissan
189 and Tulnacross join the Ballinderry mainstream from the left while the Kingsmill, Killymoon Claggan
190 and Kildress join from the right. The Ballymully and Rock are left bank rivers to the Lissan and
191 Killymoon Claggan respectively. Thanks to the topological nature of the diagram, adjacent rivers in
192 nearby rows on the diagram do not necessarily imply a closer spatial relationship in reality. This
193 flexibility helps to optimise the river layout which displays most information with less rows (see Figure
194 1d and e). The rivers connect only with vertical dashed lines ending with black solid dots. Their lengths
195 in the diagram represents relative lengths and monitoring sites are plotted on their relative positions
196 on rivers, with a scale bar in the bottom-right corner for reference.

197 3.2 Visualising quantitative variables on river networks

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

209 control exposed by this function also allows, for example in Figure 3, the direction of the triangles to
210 indicate relative positions of the tributaries.

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

222 3.3 Visualising qualitative/semi-quantitative variables on river networks

223 Figure 4 shows hydromorphological conditions of the rivers in 2009, which were evaluated according
224 to River Hydromorphological Assessment Technique (RHAT) (NIEA, 2009). The RHAT measures
225 hydromorphological naturalness using eight variables, and each variable is evaluated by a five-level
226 system: High, Good, Moderate, Poor and Bad. In Figure 4, a block-chart is generated by
227 `RiverBlock()`: four selected hydro-morphological quality variables are displayed, these being
228 Channel Vegetation, Channel Flow, Bank Vegetation and Riparian land-use. The last two variables
229 were evaluated for both left and right banks of the rivers. River reaches can be highlighted with
230 different colours to represent different reach characteristics. The Upper Ballinderry Special Area of
231 Conservation (SAC) is highlighted by `RiverReach()`. The Channel Vegetation and Channel Flow
232 have relatively higher grades (Good or High) in the Upper Ballinderry SAC than those of other reaches.
233 However, Bank Vegetation and Riparian Land-use display similar degrees of naturalness to the
234 reaches outside the SAC. The elevation profiles, which are plotted by `RiverPoint()`, suggest that

235 the River Lissan, especially its upper reach, has the highest elevation drop within the river basin. The
236 right tributaries of the Ballinderry River have a comparably smaller channel gradient or river drop than
237 the left tributaries, which imply lower river energy. This may also infer a difference indownstream
238 fining rates (see Rice, 1999) – the grain sizes in the right tributaries decrease slower along the river
239 than in the left tributaries of the Ballinderry River.

240

241 **3.4 Visualising qualitative/semi-quantitative variables without river networks**

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

252 **4 Potential applications**

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

258 The visualisation process follows one simple principle – variables are visualised according to their
259 measurement types instead of what they represent (see Figure 2). Each variable can be classified

260 into one of the three groups: (1) quantitative data, (2) qualitative data and (3) semi-quantitative data.
261 Quantitative (numerical) data have meaning as a measurement, such as diversity index, species
262 richness, biomass, flow velocity and total nitrogen concentration. This type of data can be visualised
263 in bar-charts or line-charts as shown in Figure 3. Qualitative (categorical) data represent
264 characteristics that fall into categories, such as channel substrate types (boulder, cobble, gravel or
265 sand, etc.), and riparian land-use types (woodland, grassland or urban development, etc.). Semi-
266 quantitative (ordinal) data also fall into categories, but with additional characteristics such a ranking
267 order. For example, percentage cover of aquatic macrophytes (e.g. 9 level ordinal scale, Baattrup-
268 Pedersen et al., 2006; Johnson et al., 2007), and ecological water quality evaluation (e.g. 5 level
269 ordinal scale, European Commission, 2000). Qualitative and semi-quantitative data are suitable for
270 block-charts as shown in Figure 4 and Figure 5.

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

278 *rivervis* diagrams showing an environmental gradient can be beneficial and helpful for identifying
279 environmental problems, and support river basin management in various ways. For example, pollution
280 from point sources (e.g. industrial discharges, septic tanks and waste water treatment plants) and
281 from diffuse sources (e.g. agricultural land and road runoff to adjacent river reaches), and incoming
282 streams which may have a distinctive pollution or dilution effect on the main channel can be plotted
283 on topological diagrams in the form of highlighted locations or reaches (see Figure 3 and Figure 4),
284 in conjunction with biological and physicochemical monitoring data (Hensley et al., 2014). This
285 juxtaposition of multiple variables graphically can help to discover relationships among pollution

286 discharge, chemical water quality and aquatic biological status. Rare, endemic, as well as alien
287 species can be plotted to identify their spatial relation with other environmental features. For example,
288 barriers along a water course can be problematic to fish passage (Bednarek, 2001; Rolls et al., 2013).
289 By mapping barriers alongside fish data, inhibiting barriers can be identified. Barriers can be sites of
290 interest plotted by `RiverSite()`, while fish communities can be described by quantitative variables
291 such as richness, abundance or other composition parameters. Visualisation can also be of siltation,
292 which may occur downstream of bank trampling and tilled land (Sidle et al., 2006). The visualisation
293 offered by `rivervis` along a river system can pin-point where the sources and sinks of sediment
294 exist (Anthony and Julian, 1999; Meade, 1982), by adding their locations on the diagrams. After all,
295 management decisions can be well informed based on visualisation or a graphic fluvial audit (Eyquem,
296 2007).

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

309 Lastly, we designed the package with the goal that it could be easily extended. As can be seen in the
310 previous example, the types of graphics that associate with a data point or line can be bar charts, line
311 charts and block charts. By design, it is possible to embed additional types of charts that may suit

312 specific use cases not already covered by current plotting functions in `rivervis`. We intend for the
313 package to be a basis for generic riverine visualisation, and envisage significant potential values in
314 re-using the topological structure offered by `RiverDraw()` and `RiverMap()`, enabling easily
315 customisable diagrams as well as wider application.

316

317 **5 Software availability**

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

325

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331

332 **References**

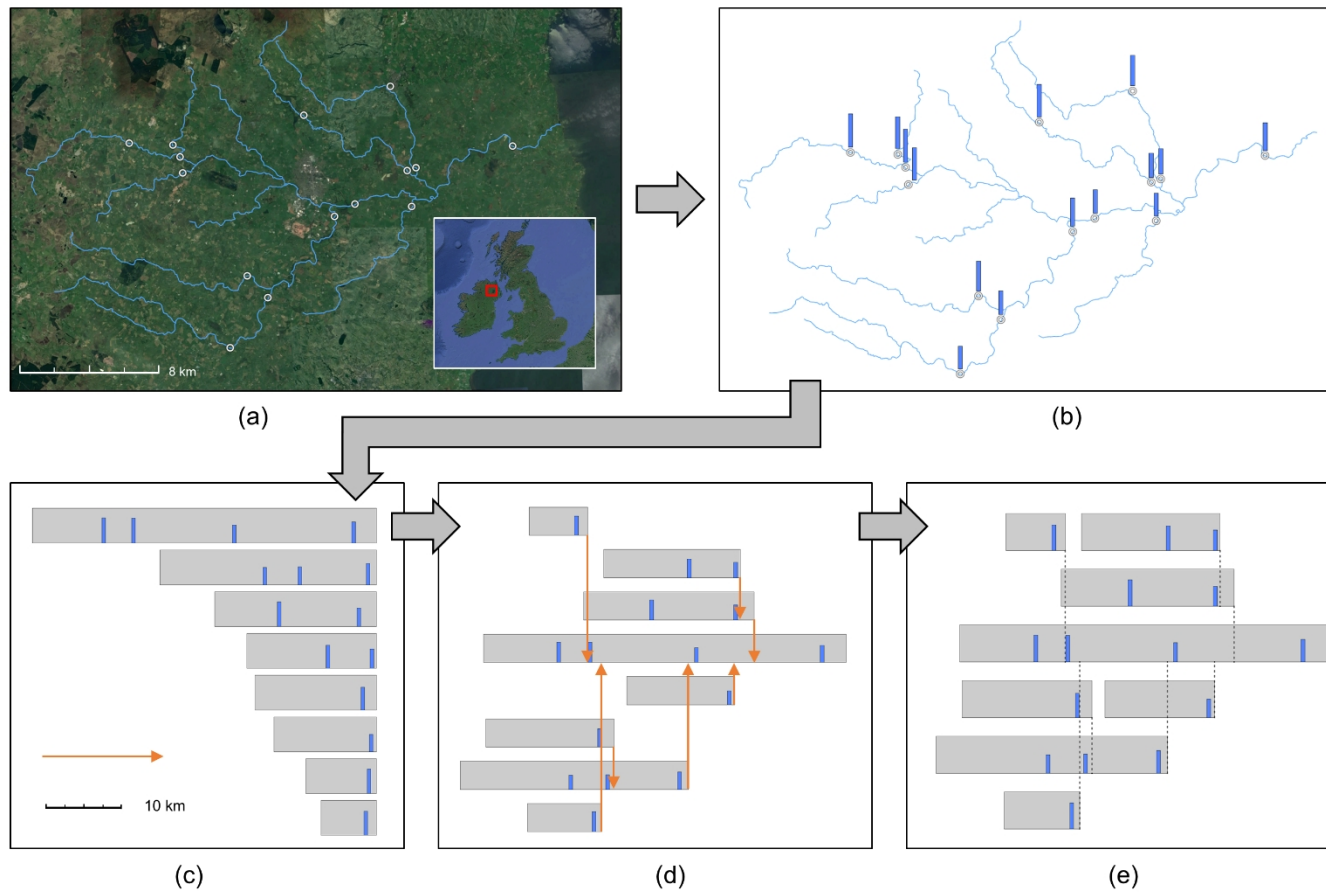
- 333 Allan, J.D., 2004. Landscapes and riverscapes: The influence of land use on stream
 334 ecosystems. *Annu. Rev. Ecol. Evol. Syst.* 35, 257–284.
 335 doi:10.1146/annurev.ecolsys.35.120202.110122
- 336 Anthony, E.J., Julian, M., 1999. Source-to-sink sediment transfers, environmental
 337 engineering and hazard mitigation in the steep Var River catchment, French Riviera,
 338 southeastern France. *Geomorphology* 31, 337–354. doi:10.1016/S0169-
 339 555X(99)00088-4
- 340 Baattrup-Pedersen, A., Szoszkiewicz, K., Nijboer, R., O'Hare, M., Ferreira, T., 2006.
 341 Macrophyte communities in unimpacted European streams: variability in assemblage
 342 patterns, abundance and diversity. *Hydrobiologia* 566, 179–196. doi:10.1007/s10750-
 343 006-0096-1
- 344 Bednarek, A.T., 2001. Undamming Rivers: A Review of the Ecological Impacts of Dam
 345 Removal. *Environ. Manage.* 27, 803–814. doi:10.1007/s002670010189
- 346 Bishop, K., Buffam, I., Erlandsson, M., Fölster, J., Laudon, H., Seibert, J., Temnerud, J., 2008.
 347 Aqua Incognita: the unknown headwaters. *Hydrol. Process.* 22, 1239–1242.
 348 doi:10.1002/hyp.7049
- 349 Borkin, M.A., Gajos, K.Z., Peters, A., Mitsouras, D., Melchionna, S., Rybicki, F.J., Feldman,
 350 C.L., Pfister, H., 2011. Evaluation of artery visualizations for heart disease diagnosis.
 351 *IEEE Trans. Vis. Comput. Graph.* 17, 2479–2488. doi:10.1109/TVCG.2011.192
- 352 BREA, 2010. Rivers and Loughs [WWW Document]. Ballinderry Rivers Trust. URL
 353 <http://www.ballinderryriver.org/index.php/trust-area/rivers-and-loughs>
 354 (accessed 11.9.18).
- 355 Brevé, N.W.P., Buijse, A.D., Kroes, M.J., Wanningen, H., Vriese, F.T., 2014. Supporting
 356 decision-making for improving longitudinal connectivity for diadromous and
 357 potamodromous fishes in complex catchments. *Sci. Total Environ.* 496, 206–218.
 358 doi:10.1016/j.scitotenv.2014.07.043
- 359 Bunn, S.E., Abal, E.G., Smith, M.J., Choy, S.C., Fellows, C.S., Harch, B.D., Kennard, M.J.,
 360 Sheldon, F., 2010. Integration of science and monitoring of river ecosystem health to
 361 guide investments in catchment protection and rehabilitation. *Freshw. Biol.* 55, 223–240.
 362 doi:10.1111/j.1365-2427.2009.02375.x
- 363 Bunn, S.E., Arthington, A.H., 2002. Basic principles and ecological consequences of altered
 364 flow regimes for aquatic biodiversity. *Environ. Manage.* 30, 492–507.
 365 doi:10.1007/s00267-002-2737-0
- 366 European Commission, 2000. Directive 2000/60/EC of the European Parliament and of the
 367 Council of 23 October 2000 establishing a framework for Community action in the field
 368 of water policy, Official Journal of the European Communities. Official Journal of the
 369 European Communities.
- 370 Eyquem, J., 2007. Using fluvial geomorphology to inform integrated river basin management.
 371 *Water Environ. J.* 21, 54–60. doi:10.1111/j.1747-6593.2006.00046.x
- 372 Fry, B.J., 2004. Computational Information Design. Massachusetts Institute of Technology.
- 373 Grainger, S., Mao, F., Buytaert, W., 2016. Environmental data visualisation for non-scientific
 374 contexts: Literature review and design framework. *Environ. Model. Softw.* 85, 299–318.

- 375 doi:10.1016/j.envsoft.2016.09.004
- 376 Hawkes, H.A., 1997. Origin and development of the biological monitoring working party score
377 system. *Water Res.* 32, 964–968.
- 378 Hensley, R.T., Cohen, M.J., Korhnak, L. V., 2014. Inferring nitrogen removal in large rivers
379 from high-resolution longitudinal profiling. *Limnol. Oceanogr.* 59, 1152–1170.
380 doi:10.4319/lo.2014.59.4.1152
- 381 Jackson, F.L., Hannah, D.M., Fryer, R.J., Millar, C.P., Malcolm, I.A., 2017. Development of
382 spatial regression models for predicting summer river temperatures from landscape
383 characteristics: Implications for land and fisheries management. *Hydrol. Process.* 31,
384 1225–1238. doi:10.1002/hyp.11087
- 385 Jackson, F.L., Malcolm, I.A., Hannah, D.M., 2015. A novel approach for designing large-scale
386 river temperature monitoring networks. *Hydrol. Res.* nh2015106.
387 doi:10.2166/nh.2015.106
- 388 Johnson, L.B., Host, G.E., 2010. Recent developments in landscape approaches for the
389 study of aquatic ecosystems. *J. North Am. Benthol. Soc.* 29, 41–66.
- 390 Johnson, R.K., Furse, M.T., Hering, D., Sandin, L., 2007. Ecological relationships between
391 stream communities and spatial scale: implications for designing catchment-level
392 monitoring programmes. *Freshw. Biol.* 52, 939–958. doi:10.1111/j.1365-
393 2427.2006.01692.x
- 394 Kail, J., Brabec, K., Poppe, M., Januschke, K., 2015. The effect of river restoration on fish,
395 macroinvertebrates and aquatic macrophytes: A meta-analysis. *Ecol. Indic.* 58, 311–
396 321. doi:10.1016/j.ecolind.2015.06.011
- 397 Keim, D., Andrienko, G., Fekete, J., Görg, C., Kohlhammer, J., Melançon, G., 2008. Visual
398 Analytics: Definition, Process, and Challenges, in: *Information Visualization*. Springer
399 Berlin Heidelberg, Berlin, Heidelberg, pp. 154–175. doi:10.1007/978-3-540-70956-5_7
- 400 Kondolf, G.M., Boulton, A.J., O'Daniel, S., Poole, G.C., Rahel, F.J., Stanley, E.H., Wohl, E.,
401 Bång, A., Carlstrom, J., Cristoni, C., Huber, H., Koljonen, S., Louhi, P., Nakamura, K.,
402 2006. Process-based ecological river restoration: Visualizing three-dimensional
403 connectivity and dynamic vectors to recover lost linkages. *Ecol. Soc.* 11. doi:10.5751/ES-
404 01747-110205
- 405 Lake, P.S., Bond, N., Reich, P., 2007. Linking ecological theory with stream restoration.
406 *Freshw. Biol.* 52, 597–615. doi:10.1111/j.1365-2427.2006.01709.x
- 407 Mao, F., Shi, Y., Richards, K., 2014. rivervis: River Visualisation Tool. *Compr. R Arch. Netw.*
- 408 Meade, R., 1982. Sources, sinks, and storage of river sediment in the Atlantic drainage of the
409 United States. *J. Geol.* 90, 235–252.
- 410 NIEA, 2014. Neagh Bann: Draft River Basin Management Plan. Lisburn.
- 411 NIEA, 2009. River Hydromorphology Assessment Technique (RHAT) training guide (2009).
- 412 NIEA, 2008. Neagh Bann: Draft River Basin Management Plan. Lisburn.
- 413 Ozerol, G., Newig, J., 2008. Evaluating the success of public participation in water resources
414 management: Five key constituents. *Water Policy* 10, 423. doi:10.2166/wp.2008.001
- 415 Pocock, M.J.O., Evans, D.M., Fontaine, C., Harvey, M., Julliard, R., McLaughlin, Ó.,
416 Silvertown, J., Tamaddoni-Nezhad, A., White, P.C.L., Bohan, D.A., 2016. The
417 Visualisation of Ecological Networks, and Their Use as a Tool for Engagement,

- 418 Advocacy and Management, *Advances in Ecological Research*.
419 doi:10.1016/bs.aecr.2015.10.006
- 420 Poole, G.C., 2010. Stream hydrogeomorphology as a physical science basis for advances in
421 stream ecology. *J. North Am. Benthol. Soc.* 29, 12–25. doi:10.1899/08-070.1
- 422 Quevauviller, P., Balabanis, P., Fragakis, C., Weydert, M., Oliver, M., Kaschl, A., Arnold, G.,
423 Kroll, A., Galbiati, L., Zaldivar, J.M., Bidoglio, G., 2005. Science-policy integration needs
424 in support of the implementation of the EU Water Framework Directive. *Environ. Sci.*
425 *Policy* 8, 203–211. doi:10.1016/j.envsci.2005.02.003
- 426 Ran, L., Tian, M., Fang, N., Wang, S., Lu, X., Yang, X., Cho, F., 2018. Riverine carbon export
427 in the arid-semiarid Wuding River catchment on the Chinese Loess Plateau.
428 *Biogeosciences Discuss.* 1, 1–23. doi:10.5194/bg-2018-51
- 429 Raymond, B., Hosie, G., 2009. Network-based exploration and visualisation of ecological
430 data. *Ecol. Modell.* 220, 673–683. doi:10.1016/j.ecolmodel.2008.12.011
- 431 RC Team, 2013. R: A language and environment for statistical computing. *R Found. Stat.*
432 *Comput.*
- 433 Rice, S., 1999. The nature and controls on downstream fining within sedimentary links. *J.*
434 *Sediment. Res.* 69, 32–39. doi:10.2110/jsr.69.32
- 435 Rice, S.P., Church, M., 2001. Longitudinal profiles in simple alluvial systems. *Water Resour.*
436 *Res.* 37, 417–426. doi:10.1029/2000WR900266
- 437 Rice, S.P., Greenwood, M.T., Joyce, C.B., 2001. Macroinvertebrate community changes at
438 coarse sediment recruitment points along two gravel bed rivers. *Water Resour. Res.* 37,
439 2793–2803. doi:10.1029/2000WR000079
- 440 Rolls, R.J., Ellison, T., Faggotter, S., Roberts, D.T., 2013. Consequences of connectivity
441 alteration on riverine fish assemblages: potential opportunities to overcome constraints
442 in applying conventional monitoring designs. *Aquat. Conserv. Mar. Freshw. Ecosyst.* 23,
443 624–640. doi:10.1002/aqc.2330
- 444 Sarkar, D., 2008. *Lattice: Multivariate Data Visualization with R*. Springer New York, New
445 York.
- 446 Schmidt, M., 2008. The Sankey diagram in energy and material flow management: Part I:
447 History. *J. Ind. Ecol.* 12, 82–94. doi:10.1111/j.1530-9290.2008.00004.x
- 448 SEPA, 2014. *The Water Environment (Controlled Activities) (Scotland) Regulations 2011*.
- 449 Sidle, R.C., Ziegler, A.D., Negishi, J.N., Nik, A.R., Siew, R., Turkelboom, F., 2006. Erosion
450 processes in steep terrain—Truths, myths, and uncertainties related to forest
451 management in Southeast Asia. *For. Ecol. Manage.* 224, 199–225.
452 doi:10.1016/j.foreco.2005.12.019
- 453 Spruill, T.B., Harned, D.A., Ruhl, P.M., Eimers, J.L., McMahon, G., Smith, K.E., Galeone,
454 D.R., Woodside, M.D., 1998. Nutrients in Streams and Ground Water, in: *Water Quality*
455 *in the Albemarle-Pamlico Drainage Basin, North Carolina and Virginia, 1992-95*.
456 doi:10.3133/cir1157
- 457 Stoffel, M., Rice, S., Turowski, J.M., 2013. Process geomorphology and ecosystems:
458 Disturbance regimes and interactions. *Geomorphology* 202, 1–3.
459 doi:10.1016/j.geomorph.2013.06.018
- 460 Vannote, R., Minshall, G.W., Cummins, K.W., Sedell, J.R., Cushing, C.E., 1980. The river

- 461 continuum concept. *Can. J. Fish. Aquat. Sci.* 37, 130–137.
- 462 Vannote, R.L., 1980. The River Continuum Concept. doi:10.1139/f80-017
- 463 Ward, J. V., Tockner, K., Arscott, D.B., Claret, C., 2002. Riverine landscape diversity. *Freshw.*
464 *Biol.* 47, 517–539. doi:10.1046/j.1365-2427.2002.00893.x
- 465 White, J.C., Hannah, D.M., House, A., Beatson, S.J.V., Martin, A., Wood, P.J., 2017.
466 Macroinvertebrate responses to flow and stream temperature variability across regulated
467 and non-regulated rivers. *Ecohydrology* 10, 1–21. doi:10.1002/eco.1773
- 468 Wickham, H., 2009. *ggplot2: elegant graphics for data analysis*. Springer New York.
- 469 Wohl, E., 2017. Connectivity in rivers. *Prog. Phys. Geogr.* 41, 345–362.
470 doi:10.1177/0309133317714972

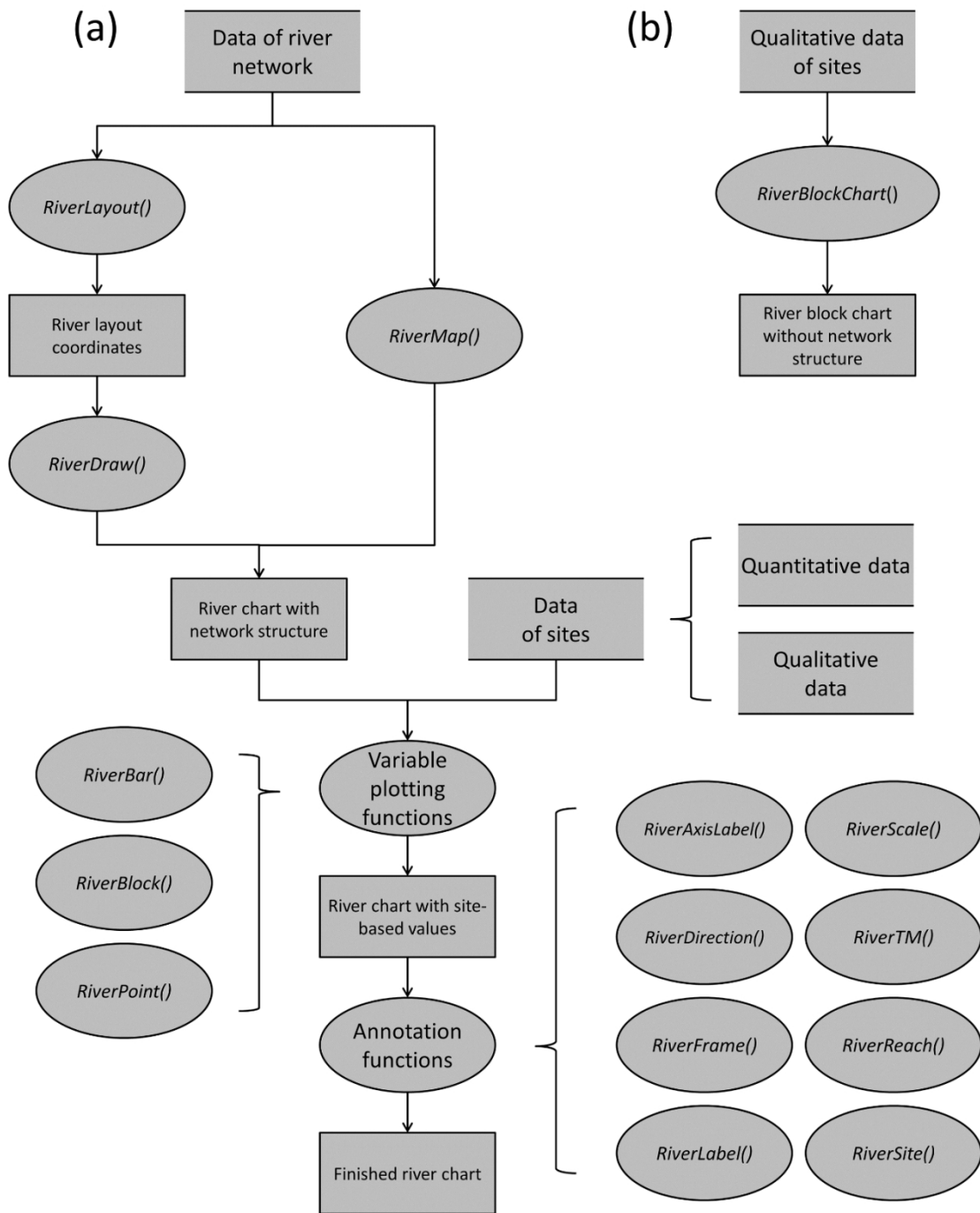
472 **Figures**



473

474 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
475 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.
476 (b) Main Ballinderry streams with bars showing parameter values at each sampling sites. (c) Unconnected Ballinderry streams that have sampling sites. The
477 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
478 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
479 previous step.

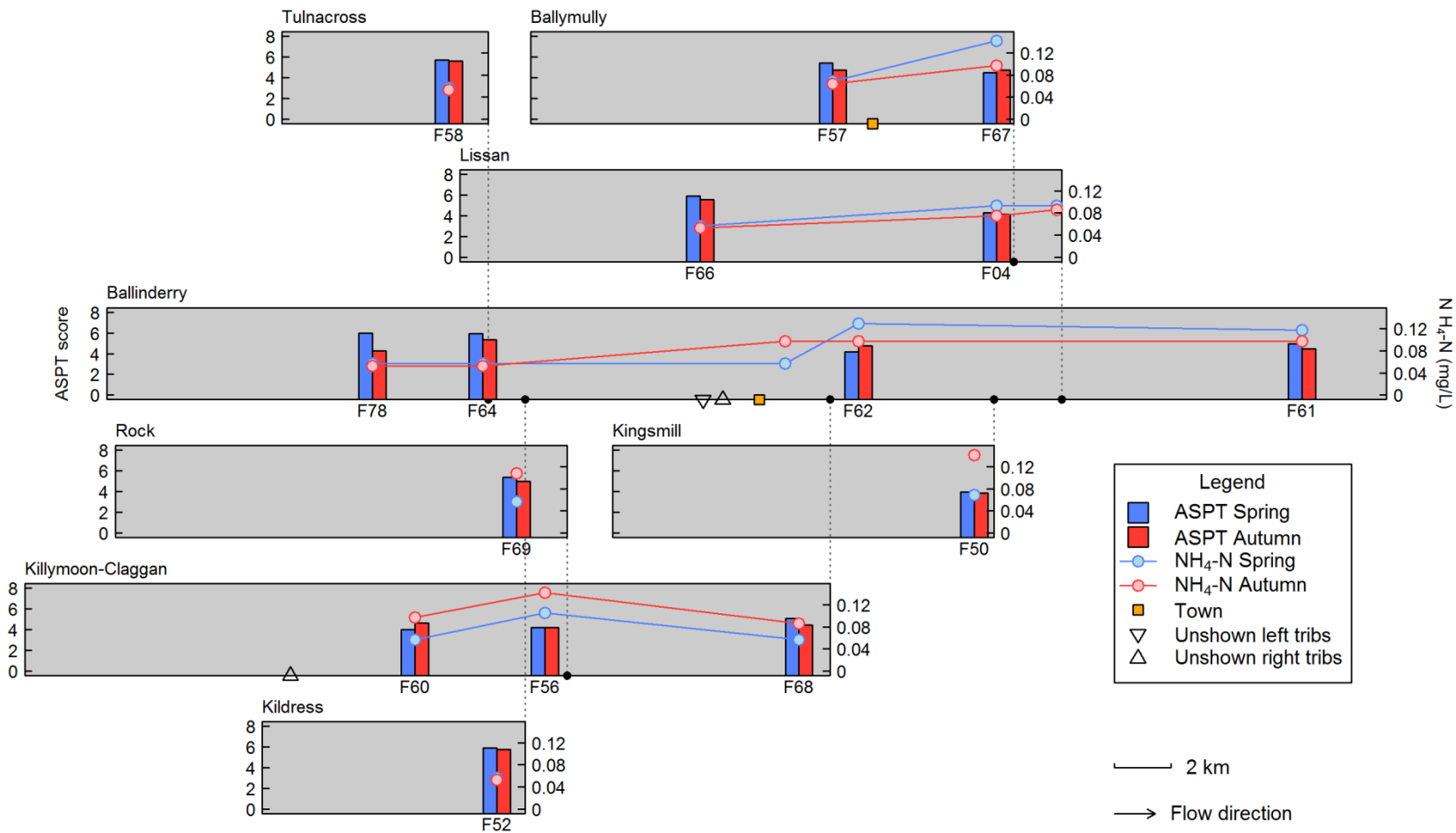
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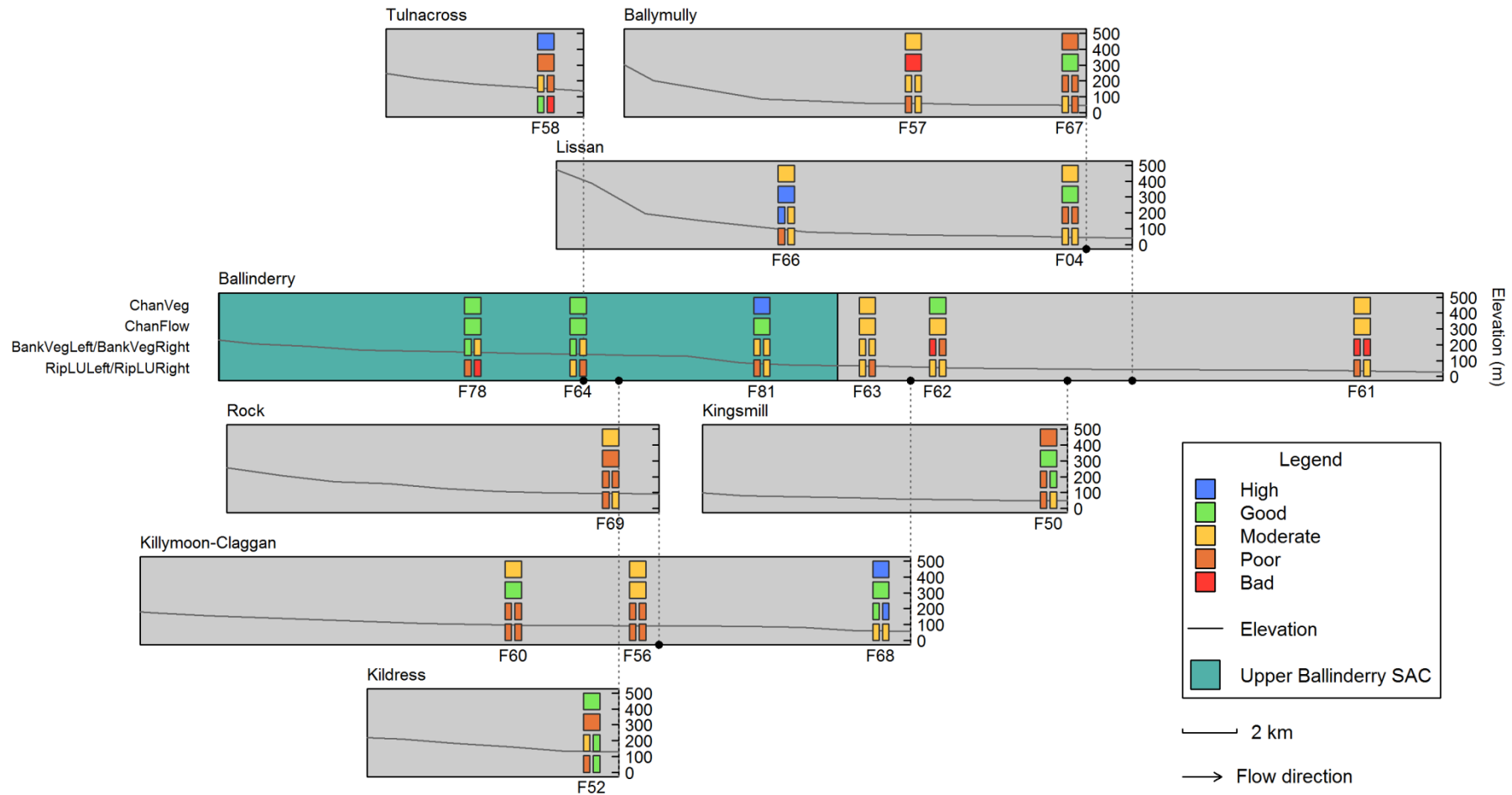
482 Figure 2. Workflow of the R package `rivervis`. The ellipses denote functions; the boxes with two horizontal
 483 lines denote files or data; and the closed boxes denote input or output. (a) Workflow for diagrams with showing
 484 river network structure; (b) workflow for diagrams without river network.

485



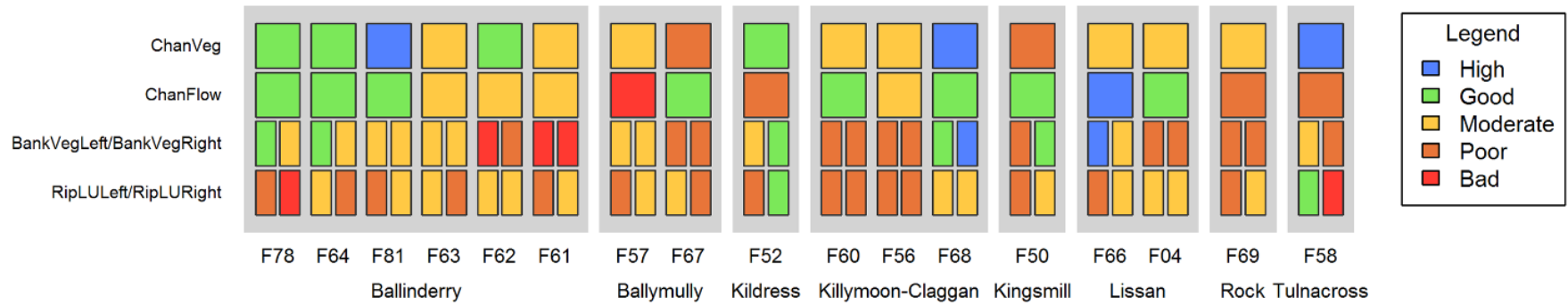
486

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



491

492 Figure 4. Example diagram produced by *rivervis* for qualitative/semi-quantitative variables in the Ballinderry River Basin. The black circles with dashed lines
 493 denote the location on the rivers where their tributaries join them. Four variables, including Channel Vegetation, Channel Flow, Bank Vegetation and Riparian
 494 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,
 495 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
 496 Framework Directive. In addition, elevation profile and the Upper Ballinderry Special Area of Conservation (SAC) are also shown in the diagram.



497

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

501

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