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River Architect

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ABSTRACT

River design is often conceptually approached aiming at either physical channel stability or ecological functionality. We present a novel concept within an open-source software called River Architect that addresses both these goals and estimates costs. River Architect is flexible for site- and application-specific characteristics, with modules for the analysis and design of habitat-enhancing and channel-stabilising feature groups. Ecological assets are assessed as a function of a novel metric that incorporates the seasonal and discharge-dependent preferred habitat area of target species. Calculations of cost estimates and ecological efficiency are illustrated by an example in a gravel-cobble-bed river.

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Code metadata

Current code version	*v01.1*
Permanent link to code/repository used of this code version	https://github.com/ElsevierSoftwareX/SOFTX_2019_277
Code Ocean compute capsule	*Not applicable; for test-running the code please download from our sample data repository:* https://github.com/RiverArchitect/SampleData
Legal Code License	*BSD 3-Clause "New" or "Revised" license (BSD-3-Clause)*
Code versioning system used	*git*
Software code languages, tools, and services used	*Python3*
Compilation requirements, operating environments & dependencies	*ArcGIS Pro Conda environment*
If available Link to developer documentation/manual	https://riverarchitect.github.io/RA_wiki/
Support email for questions	https://github.com/RiverArchitect/program/issues/

Software metadata

Current software version	*1.1*
Permanent link to executables of this version	https://github.com/RiverArchitect/program/releases/tag/v1.1
Legal Software License	*BSD 3-Clause "New" or "Revised" license (BSD-3-Clause)*
Computing platforms/Operating Systems	*Microsoft Windows*
Installation requirements & dependencies	*ArcGIS Pro*
If available, link to user manual — if formally published include a reference to the publication in the reference list	https://riverarchitect.github.io
Support email for questions	river.architect.program@gmail.com

1. Motivation and significance

River management involves balancing among societal uses of water, ecological improvements, physical sustainability, cost, and public perceptions about idealised river aesthetics [1]. A great challenge lies in the trade-off between flood resilience and

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habitat enhancement within self-sustaining river systems [2,3]. Common eco-physical success metrics involve aquatic species lifestage abundances, hydraulic complexity, habitat suitability, or the longevity of installed river design features [4–6]. Scientific software developments, such as CASiMiR [7], HEC-EFM [8], or MesoHABSIM [9], use geographic information systems (GIS), hydrologic and ecological data, and hydraulic modelling to inform habitat suitability assessments. Algorithms such as *RiverScape* [10] or *CONCEPTS (HEC-RAS)* [11] fit flood protection features into river landscapes using hydraulic parameters. Habitat enhancement and flood protection designs use common design features, such as side channel construction, floodplain grading (lowering of disconnected riparian zones), or embankment (berm) modifications [12,13]. Moreover, the parametrisation of habitat enhancing river design features enables the definition of survival thresholds to determine feature lifespans [14]. Many more algorithmic methods are available for designing river modifications [15], including morphological assets of rivers such as channel bedforms [16]. Procedural generation creates designs algorithmically instead of manually (including by computer-aided design, CAD). This requires the translation of design strategies, including novel concepts that merge ecohydraulics, geomorphology, and hydraulic engineering, into parametric algorithms. We developed a Python-based software called *River Architect* to address interdisciplinary river design challenges on a river reach scale (<1000 channel widths). *River Architect* builds on a deterministic procedural design concept for river assessment and design. It comes with a graphical user interface (GUI) that provides users with the options of importing data, assessing physical lifespans of river design features, generating self-sustaining riverscapes, calculating and comparing ecohydraulic efficiency metrics, and estimating construction quantities and costs for specific sites. The procedural design integrates existing codes (e.g., *River Builder* [17]) and scientific procedures (e.g., Lifespan mapping [18]), and was developed based on multiple potential project sites at a gravel-cobble bed river in California.

2. Software description

2.1. Software architecture and workflow

River Architect uses a novel roadmap-concept for ecological and sustainable river design (Fig. 1) that is implemented in a *Python 3*-based GUI with hierarchical tabs. Five tabs guide the preparation of input files, lifespan mapping, morphological design, ecohydraulic assessments, and project metrics calculation. Expert assessment is required for preparing a digital elevation model (DEM) of the terrain that serves for two-dimensional (2D) hydrodynamic modelling (the supplemental material contains more information on 2D modelling). Workbooks enable flexible and organised user specifications of flow duration curves, threshold values, and ecohydraulic (*Physical Habitat*) functions.

Similar to the construction procedure of a house, *River Architect*'s roadmap begins with the assessment and design of the morphological framework, proceeds with river "furniture" (plantings and other nature-based engineering features), and concludes with plugging (connecting) the new design into a hydro-geomorphological framework. Constructive river design features are defined in a "Features" workbook as a function of survival threshold values applied to the following geospatial datasets and parametric derivatives:

- Hydraulics: Flow depth (length units) and velocity (length per second) magnitudes and directions from steady 2D modelling of at least three flood discharges for lifespan analyses and three discharges within the annual range for habitat assessments (e.g., baseflow, mean annual and mean annual maximum flow); the most precise results are obtained when using bins of mean daily discharge, which can lead to long calculation times;
- A DEM (length units) with high enough resolution to capture sub-width-scale morphodynamics (more information in the supplemental material);
- Sediment facies map with grain size (length units) classification [19] (more information in the supplemental material);
- Topographic change rates (optional, in length units) with pixel-specific information about scour and fill, either based on past observations (supplemental material) or morphodynamic model predictions (e.g., Nays2DH [20]; the UBC regime model [21]; or RIVERMorph [22]).

River Architect combines input rasters into dimensionless parameter rasters to compute grain mobility rasters as a function of critical dimensionless bed shear stress (Shields, 1936), and streamwood mobility as a function of the Froude number [23,24]. The supplemental material describes the formulae used for both critical grain sizes and wood log diameters.

Terraforming (morphological adjustment) defines the landscaping framework at a functional-unit scale [25]. The basic installation of *River Architect* comes with default threshold values for five terraforming features including grading, backwater creation, river widening (berm setback), artificial side cavities, and side channel creation [14]. *River Architect* identifies suitable regions for threshold-based terraforming considering feature lifespans, but only as on–off features. Therefore, expert assessment is required to draw new terraforms using CAD. Moreover, synthetic, near-natural river landscapes can be procedurally generated with the *River Builder* code [17]. The modified DEM is then run in a 2D hydrodynamic model to iteratively verify that ecohydraulic goals (e.g., target flow velocity and depth for indigenous fish) and flood protection requirements are met. Once a new DEM has been created, the necessary terraforming volumes (excavation and fill) can be calculated in the Volume Assessment tab for the later on cost assessment.

Vegetation plantings stabilise new terraforms and provide valuable cover habitat (micro turbulences induced by roughness elements) for aquatic and riverine species [26,27]. Nature-based engineering techniques (e.g., anchored streamwood, angular boulders or geotextile) further stabilise new terraforms and increase the survival chances of plantings immediately after construction, when the root strength is most limited [28,29]. Fig. 1 shows the successive application of vegetation plantings and nature-based engineering to the new DEM, starting with the creation of a new "Modified Condition".

Ecohydraulic assessment of available habitat area and connectivity is performed for the initial condition and the ecomorphologically optimised new DEM with or without cover elements such as plantings and other nature-based engineering features.

The resilience of any terraforming feature depends on its self-maintenance capacity. Self-maintenance requires that the inflowing and outflowing sediment fluxes of a site are equilibrated. If a final design shows to be net erosional, gravel augmentation is a possible remedy [30]. *River Architect* indicates suitable locations for gravel stockpiles or injections (not indicated in Fig. 1).

A Project Maker module crops the optimised geospatial datasets to site-specific extents ("Project Area" in Fig. 1) and estimates construction cost at an initial planning level of uncertainty. A summary workbook with cost-relevant quantities, rough cost estimates and an ecological efficiency metric constitutes the final product.

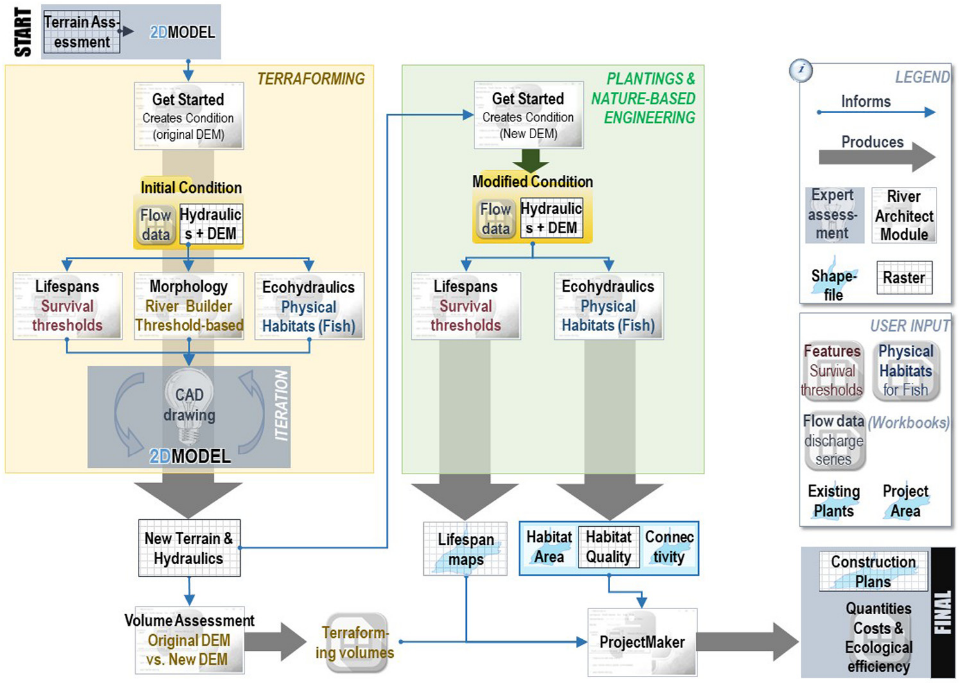

Fig. 1. The new river design concept with nested application of River Architect's modules, 2D hydrodynamic modelling (2D model), and expert assessment. The arrows indicate functional relationships, which may have an informative (successor receives information) or a productive (predecessor generates data) character. A UML-based activity diagram is available in the supplementary material.

2.2. Software functionalities and data products

The functional core of *River Architect* steps in after optional preparation of other geospatial datasets that can be generated within the Get Started tab:

- A detrended DEM (length units) raster containing relative terrain elevation above the river Thalweg;
- A depth-to-water-table (length units) raster in the vicinity of a river corresponding to baseflow water surface elevation; and
- A morphological-unit (text) raster delineating river landforms [31] (more information is available in the supplemental material).

River Architect's Ecohydraulics module produces ecological efficiency metrics as a function of hydraulic (flow depth and velocity) and cover Habitat Suitability Indices (*HSI*s) for user-specified target fish species and lifestages. The flow depth, velocity, and cover indices estimate each pixel's habitat quality. The *HSI* varies between values of 0.0 to 1.0 indicating organism avoidance to preference, respectively. The cover habitat suitability index (HSI_{cov}) may refer to various forms of cover, such as substrate grain size, vegetation, boulders, or streamwood [32–34]. *River Architect* applies the HSI_{cov} as the maximum value of cover types [35]. The combination of the *HSI*s constitutes the composite (or combined) Habitat Suitability Index (*cHSI*). The *cHSI* may be either the product of the depth, velocity and cover *HSI* or their arithmetic or geometric mean [36,37] at user discretion, with geometric mean the default.

Useable habitat area is calculated as the sum of the pixel area where the *cHSI* value exceeds a user-specified threshold ϑ (default: $\vartheta = 0.5$ according to [38]) and for every discharge where hydraulic datasets are available. *River Architect* is mindful that species grow, and discharges change through the year. Therefore, it multiplies useable habitat area for each discharge by the relative duration p_{Qk} of that discharge during the season that is relevant to the target species' lifestage. River Architect automatically calculates p_{Qk} for provided discharges and flow duration curves. The sum of relative habitat areas over all relevant discharges of a season produces the ecohydraulic efficiency parameter "Seasonal Habitat Area" (*SHArea* in length units to the square).

$$SHArea = \sum_{p_{Qk}}^{p_{Qn}} \left[\sum pixels\,(cHSI > \vartheta) \right] \cdot p_{Qk} \tag{1}$$

where subscript n represents the number of discharges considered and subscript k is the counter up to the *nth* discharge. Fig. 2 illustrates the calculation procedure of *SHArea*, considering that hydrodynamic datasets of four discharges were produced with 2D modelling.

Similar weighting as a function of a river's flow duration curve was used in other studies [36,39], but the practice-oriented *SHArea* calculation implemented in *River Architect* is novel.

A Connectivity tab aids to identify locations and discharges at which species-specific habitat area patches become disconnected from the main channel. An area is considered disconnected if no wetted path, which fulfils species-specific requirements, connects an area patch to the main channel. Moreover, fish can swim downstream in strong currents, but not upstream (anisotropic effects of swimming speed). Velocity direction datasets help to detect and exclude directional paths where anisotropic effects of swimming speed apply. Thus, connectivity analysis produces maps of fish stranding risks with labels that indicate the highest discharge up to which an area patch is disconnected from the main channel.

Lifespan mapping evaluates physical longevity of terraforming, vegetation plantings, other nature-based engineering, and sediment connectivity features as a function of threshold values. Users can define threshold values of features for dimensionless bed shear stress, depth to water table, relative elevation (detrended DEM), flow depth, velocity, Froude number, substrate grain size, morphological units, terrain slope, and topographic

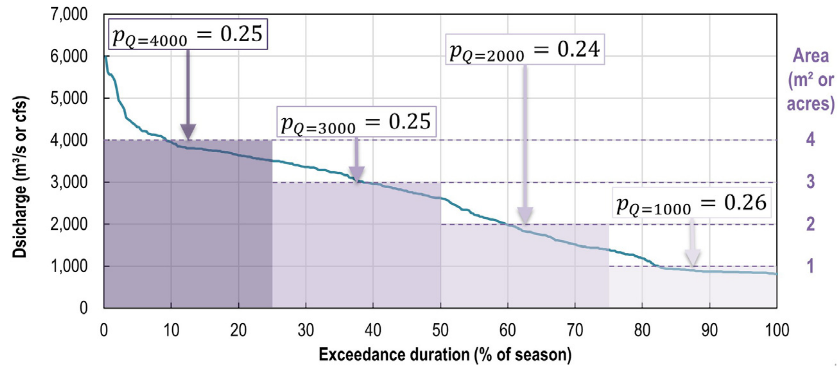

Fig. 2. *SHArea* calculation scheme example using outputs from 2D-modelled discharges (1000, 2000, 3000, and 4000 m^3/s or cfs for representative purposes) and their relative duration p_{Qk} during the relevant season of a target fish species' lifestage. Use of more discharges yields a more precise calculation.

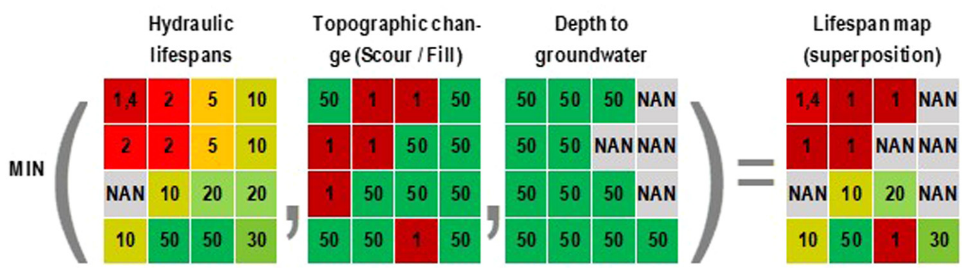

Fig. 3. Illustration of the lifespan mapping procedure (synthetic data): The hydraulic lifespans (in years) result from the spatial comparison of 2D modelling results. Annual topographic change rates indicate if a feature survives at least one year; otherwise, a maximum topographic lifespan of 50 years is assigned here. The depth to groundwater determines the applicability of plantings or bioengineering features as an on/off function, where non-relevant pixels are assigned a not-a-number (NAN) value and relevant pixels a maximum value of 50 years. The minimum of the superposition of the parameter-specific lifespan rasters constitutes a feature lifespan map [14,18]. Users can toggle on and off the application of hydraulic, topographic change and depth to groundwater thresholds that restrict lifespan mapping.

change. Features can be mobilised or destroyed by flood discharges, when the pixel value of a threshold parameter is exceeded [18]. Thus, mobilisation (or destruction) of features occurs when one or more hydrodynamic variables exceed user-defined threshold values (Fig. 3).

An intermediate step of the lifespan mapping procedure creates rasters with potentially stable grain sizes or streamwood diameters, which are related to a user-defined discharge. Such information may be relevant for required dimensions of bioengineering features such as boulders or streamwood. *River Architect* saves such information for user-defined discharges as "Design maps".

Survival thresholds of singular features within each of the four feature groups vary, and therefore, preferable features with highest lifespans can be determined for every group with the Lifespan module's Max Lifespan tab. Fig. 4 qualitatively illustrates the process of determining the most suitable plantings within the feature group "Vegetation Plantings", if three different plant species were compared. The overlay of the maximum lifespan raster and a shapefile containing information on the features that have the maximum lifespan is what we refer to as "maximum lifespan map".

River Architect's Morphology module (Modify Terrain tab) enables automated grading of disconnected floodplains or bars, and relevant areas for river widening (berm setback) based on depth-to-water-table thresholds for vegetation plantings or relative berm height. Grading may enhance many functions, where returning the relative terrain elevation (detrended DEM) to a height above the water table that can support phreatic plant species is an example.

Using *River Builder* [17] within *River Architect* enables the creation of new, near-natural synthetic river channels. Users estimate reach-scale hydro-geometric parameters and then optionally turn on as many geometric functions (e.g., sine or tangent) as they want to create nature-like sub-reach-scale undulations of channel form pattern. Synthetic fluvial landscapes produced with *River Builder* need to be manually fitted into real terrains for actual engineering applications (e.g., creating a side channel or eco-functional flood bypass).

The Project Maker module uses retail unit costs and construction-relevant quantities such as terraforming volumes, planting area, and other nature-based engineering areas to estimate initial planning-level or relative costs for implementing the virtual river design produced within the other modules. The cost estimate is vetted against ecological benefit in terms of *SHArea* to calculate a project effectiveness metric called "Costs per *SHArea* unit gained". This metric represents the costs for one m^2 gained in the seasonal habitat area for a target fish species' lifestage compared with the initial condition. Users may customise costs based on their own expertise or local and regional business setting. In particular, target-specific cost calculation requirements (e.g., for permitting purposes) cannot be automatically calculated with *River Architect*.

3. Application example

River Architect has been developed in the framework of habitat enhancement efforts along a 37.5-km segment of California's lower Yuba River. Fig. 5 illustrates a hypothetical application of *River Architect* to a site located 29 km upstream of the river mouth (more information is available in the supplemental material). Lifespan maps for terraforming informed initial terrain design, which was then iteratively optimised per Fig. 1. Lifespan maps for plantings and other nature-based engineering features were applied to the new geospatial datasets after terraforming. Backwater habitat connectivity was ensured down to 25 m^3/s (low flow conditions). The Project Maker Module was used to produce a

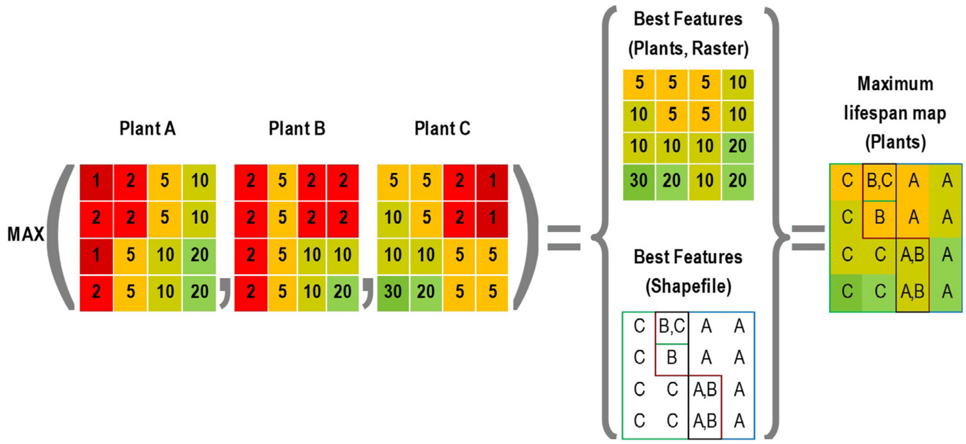

Fig. 4. Illustration of maximum lifespan mapping for the identification of most suitable features within a feature group. The example uses synthetic lifespan rasters of three plant species A, B, and C, writes the highest (maximum) lifespans to a "Best Features" raster and stores information about applicable features in a shapefile. The overlay of the "Best Features" raster and shapefile constitute the maximum lifespan map for the feature group.

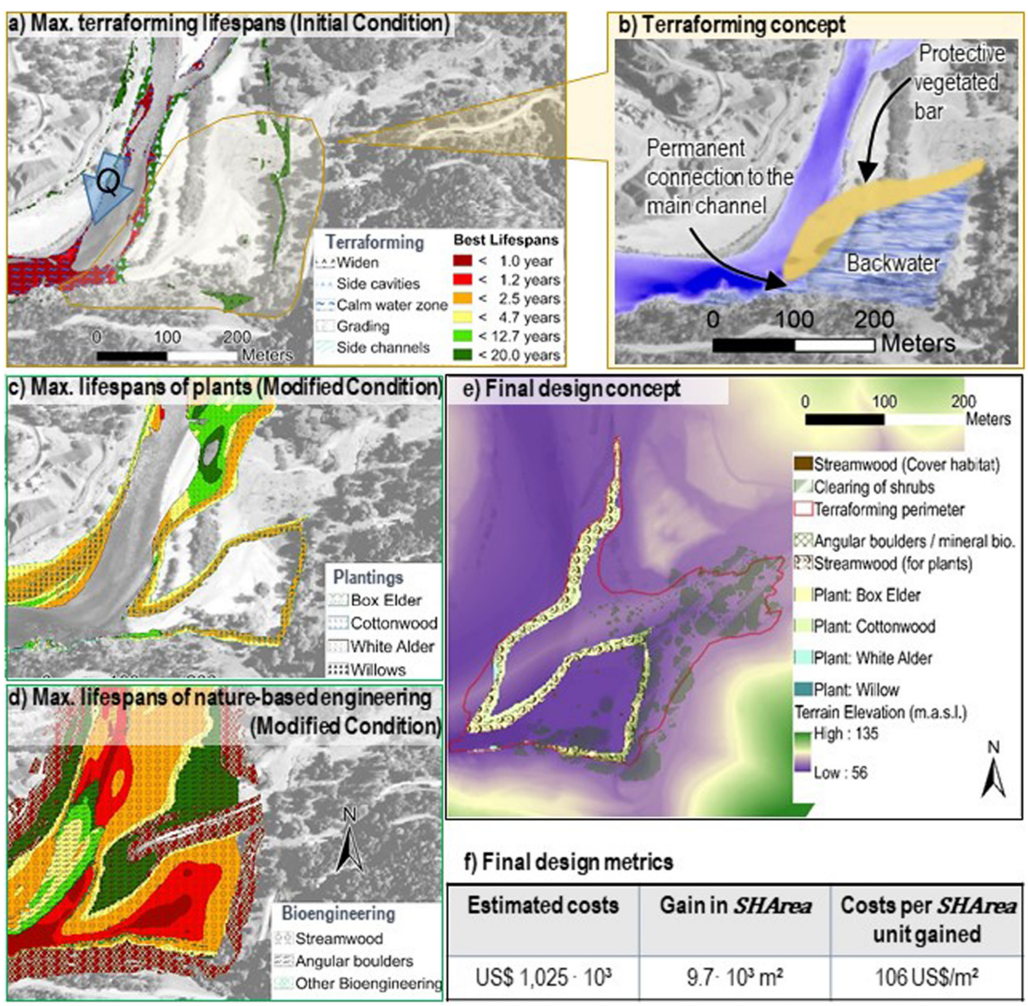

Fig. 5. River Architect applied to a site at the lower Yuba River (California, USA). Lifespan mapping of terraforming features (a) informed the development of a terraforming concept (b), which includes a protective bar to increase the lifespan of a backwater zone with optimised hydraulic conditions for juvenile Pacific salmon. The Max Lifespan module provided lifespan maps of indigenous plant species (c - Box Elder, Cottonwood, White Alder, and Willows) and other nature-based engineering features (d- Streamwood, Angular boulder, and Others such as geotextiles). The Ecohydraulics module informed the terraforming process and provided habitat suitability and connectivity maps. The Project Maker module processed the maximum lifespan maps, terraforming volumes, and ecohydraulic assessment to draw a design concept (e), and estimated the final design efficiency metrics (f). Please note that the numbers are modified for reasons of confidentiality.

final design concept within the terraforming boundaries (Fig. 5f), to estimate costs, the gain in *SHArea*, and the design efficiency (ratio of estimated costs and gain in *SHArea*).

4. Impact and conclusions

Fluvial ecomorphology and river engineering are influenced by subjective, conceptual and qualitative decision-making [13]. Higher computing power and improved algorithms enable design parametrisation and increasing levels of automation. The implementation of ecomorphological concepts in parametric decision trees, which can be understood by computers, forces logical translations of human decisions. *River Architect* pioneers in logical translation of existing methods and provides novel developments to enable design automation in river engineering and ecomorphology. One innovation of *River Architect* is the grouping and superposition of lifespan maps of design features to create physically sustainable river landscapes. Eventually, the quality of the results ultimately depends on the (in)accuracy of the input data, which River Architect processes in transparent algorithms.

The Ecohydraulics module contains multiple innovative components with the ecological efficiency metric *SHArea* and the connectivity analysis of fragmented habitats as a function of discharge. A major advantage of the *SHArea* parameter is its independent calculation method, which is based on observed seasonal discharge probabilities. Thus, in purely constructive habitat enhancement interventions, discussions about the definition of instream flow needs (e.g., [40]) become unnecessary.

With the flexible implementation of Habitat Suitability Curves and cover habitat, the Ecohydraulics module can also be applied beyond rivers for the analysis of non-aquatic flora and fauna. Hence, with River Architect not only lifespans of vegetation plantings can be calculated, but also the ecological suitability of the terrain for plant species, for example by poplar rule curves (for poplar). This application, however, represents a test scenario for the future and the comprehensive Wiki explains required modifications of preferred habitat characteristics of other species beyond the default installation.

River Architect enables half-automated design of fluvial landscapes, but terraforming remains a challenge, in particular regarding the uncertainty involved in morphodynamic modelling. For this reason, drawing new terraforms can be considered experimental design (suggested by [41]) and *River Architect* aids to run the experiment. In addition, the object-oriented, modular structure enables the flexible implementation of new and/or third-party algorithms for morphological landscape pattern at any time. For instance, the implementation of bedform analyses, based on a scale-based hierarchy and dimension approach [16] may improve terraforming on large geometric scales (<10 channel widths). Improvements in the integrity and connectivity of new terraforms at medium to small scales (>10 channel widths) can be achieved with scalable morphology and dynamic landscape models [42,43]. Moreover, water releases from dams for sustaining the downstream freshwater ecosystem (so-called environmental flows) constitute an opportunity to support channel maintenance of entire river reaches [44]. Flow optimisation requires hydro-climatic catchment assessments and can be achieved using existing codes that analyse functional flow-form relationships [45]. We aim to advance the development of the Morphology and also the Ecohydraulics module in future releases to improve the ecomorphological integrity of river landscapes produced with *River Architect*.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.softx.2020.100438.

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