2 Riparian eco-hydrodynamic habitat modelling

The availability of habitats for riparian plant species depends on climatic features and soil properties, as well as local river hydro-morphological conditions. To predict suitable habitats for the German tamarisk (Myricaria germanica), a species typical of riparian gravel banks, a large-scale ecological model was linked with a two-dimensional hydrodynamic model. This chapter includes a description of the modelling workflow, together with an application along the Moesa river (GR).

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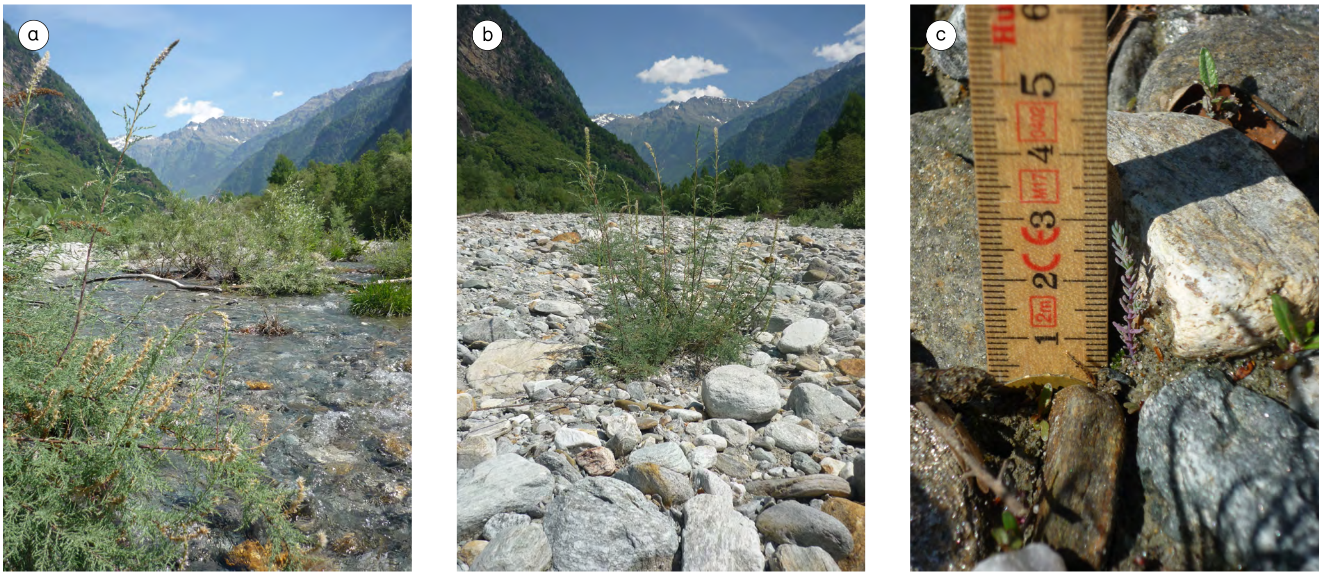
2.1 Habitat modelling in riverscapes

Riverscapes are composed of a variety of landforms, which host different habitats for terrestrial, aquatic and amphibian species. A habitat results from particular physical and biotic factors and represents a suitable location that supports the establishment, survival and reproduction of a species (Fig. 7).

The identification and quantification of habitats is crucial for the management of riverscapes. The amount and variety of habitat are linked to the biodiversity and ecological resilience of a given environment (see Chapter 5; Rachelly *et al.* 2023). Habitat analysis has practical applications for river managers, for example for evaluating the consequences of changes in environmental conditions, such as the hydrological regime (e.g. natural floods) or climate variables (e.g. temperature increase), on target plant or animal species. Examples of river habitat analysis outcomes are the identification and quantification of suitable areas for seed establishment or for fish spawning. Such results provide quantitative support to river

Figure 7

The highly dynamic riverscape along the Moesa river close to Cabbiolo (GR) harbours adult German tamarisk (Myricaria germanica) plants (a) in partially wetted areas (plant with flowers in the foreground), which also survive during dry periods. (b) Adult plants survive on gravel banks, and (c) seedlings establish on wet, sandy soil.



Photos: WSL

management decisions, such as the selection of the best spots for species conservation using the artificial sowing of seeds of an endangered plant species, or the design of more effective releases of stocked fish.

Environmental models (see Chapter 1; Fink and Scheidegger 2023) are informative, simplified representations of real-world components. They help us to understand the core elements of complex processes and can be applied at various spatial scales, from local to global. Habitat models have been applied in multiple contexts, for instance to assess the distribution of butterfly species (Maggini 2011) and the vulnerability of bird species (Maggini *et al.* 2014) in Switzerland. In the fluvial setting, models are often used to quantify fish habitats (e.g. MesoHABSIM; Parasiewicz 2011) but also vegetation succession in riverscapes (CASiMiR vegetation; Ecohydraulic Engineering GmbH 2019).

In this chapter, we propose a habitat modelling workflow for the German tamarisk (*Myricaria germanica*), a red-listed shrub species (Fig. 7). This typical pioneer plant lives on gravel banks in the dynamic riverine zone, and has specific habitat requirements depending on the particular life stage. Climate, geology, topography and hydraulics are all important for the adult shrubs. For example, frequent sediment turnover is necessary for them to avoid being outcompeted by other pioneer species such as willows (*Salix* spp.). Adults start flowering after two years if the air temperature in late spring and summer is sufficiently high. Single flood events can lead to young plants being washed away or buried. Environmental conditions therefore need to remain favourable for several years for plants to become fully established.

The seeds of the German tamarisk germinate within 24–48 h on wet sandy soil, i.e. in areas that have been inundated recently. A favourable habitat for seedling establishment has two requirements: (i) the presence of adult plants during the seed dispersal season (May to September) to ensure seed production and (ii) high inundation frequencies in the surrounding areas to support seed germination.

2.2 Linking ecological and hydrodynamic models

To predict suitable habitat for riparian species in the dynamic riverine zone, we linked two models: (i) an ecological statistical model of German tamarisk distribution and (ii) a deterministic two-dimensional hydrodynamic model for the simulation of riverine local flow conditions (see Box 4). The ecological model predicts the habitat for the German tamarisk based on large-scale (i.e. regional) climatic, geological and topographic indicators (see Chapter 1; Fink and Scheidegger 2023). The main outcome is a spatially explicit map indicating the likelihood that the target species can establish and persist in different areas. To increase the accuracy of habitat prediction for the German tamarisk, which is highly dependent on local hydrodynamic conditions, at the local (reach) scale, we linked the ecological model with a deterministic, two-dimensional hydrodynamic model (see Box 4). The resulting workflow, with the main steps and required inputs, is shown in Figure 8.

2.2.1 Ecological modelling

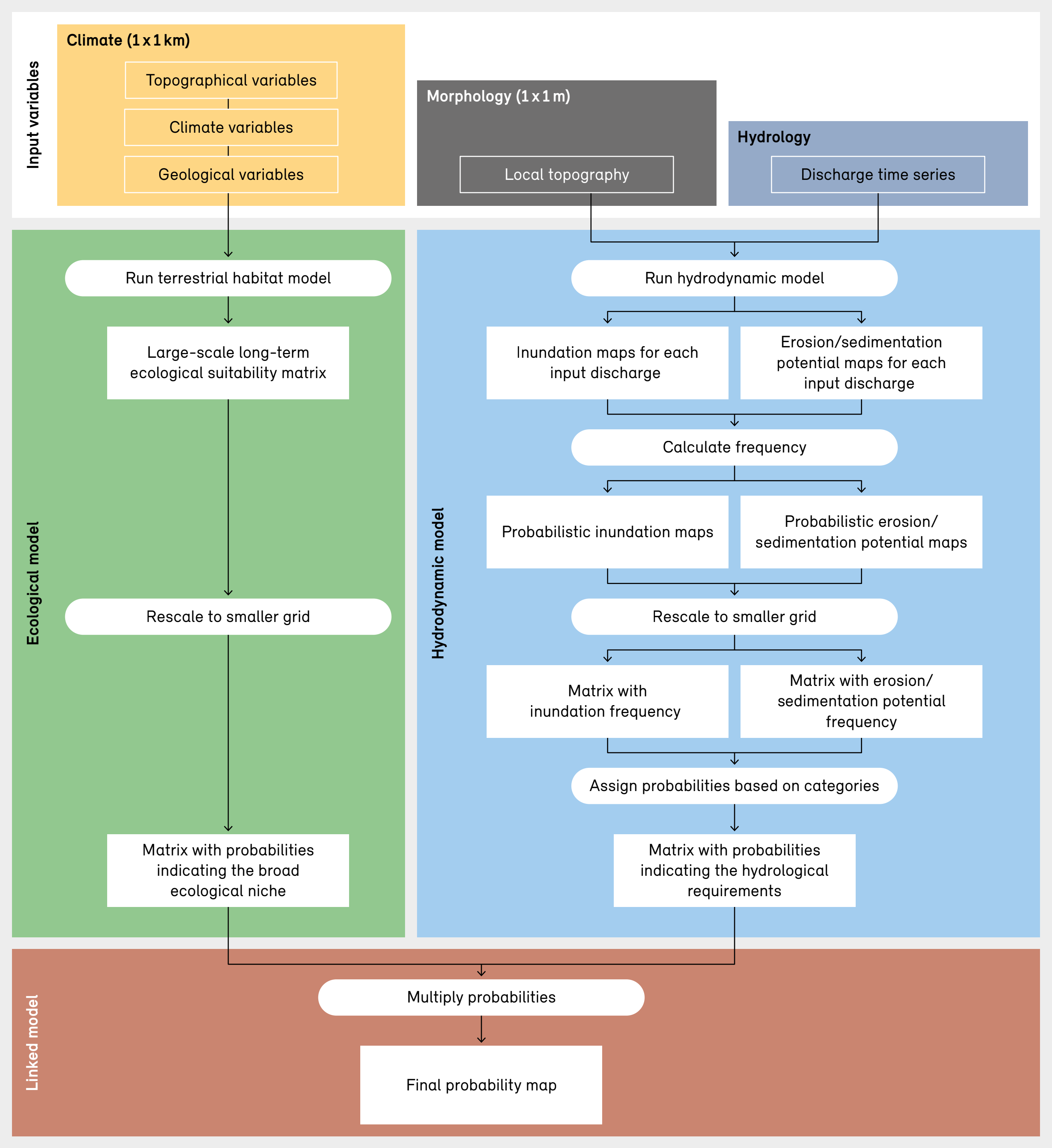
The ecological statistical habitat model for adult plants provided a large-scale habitat suitability matrix based on climatic, geological and topographic predictors. With this matrix, we could identify potentially suitable areas at a 1 × 1 km raster scale. The model used a long-term dataset covering all of Switzerland, and returned a long-term habitat suitability map for the predicted presence of German tamarisk (see Chapter 1; Fink and Scheidegger 2023).

Box 4: Hydrodynamic models

Hydrodynamic models solve a set of equations describing fluid dynamics in order to simulate water flow in rivers. In addition, hydro-morphodynamic models feature a solver to simulate the erosion and deposition of sediment along the river. Results of such simulations are the spatial distribution of flow depth and velocity, and, in the case of morphodynamic models, bed level. Hydrodynamic models require a set of input data; in this study we made use of a digital terrain model (DTM), a hydrological data series (i.e. discharge values), and an estimation of riverbed roughness. In the case of a morphodynamic simulation, extended information on sediment characteristics is needed. In Switzerland, discharge data is measured and available at many sites, whilst the remaining input data often needs to be collected ad hoc for each study site. For the hydrodynamic simulations of this study, we used BASEMENT (Vanzo *et al.* 2021), a freeware tool for the simulation of multiple river processes.

Figure 8

Workflow linking the ecological and hydrodynamic models. The results of both the ecological model and the hydrodynamic model are linked to obtain a probability map, predicting seedling habitat more accurately. The large coloured blocks represent the subsections of the methodology. The smaller rectangles represent datasets and the ovals represent actions.



Source: VAW, ETH Zurich /WSL

2.2.2 Hydrodynamic modelling

We set up and calibrated a two-dimensional hydrodynamic model of the study site (see Section 2.3) using the freeware BASEMENT (*https://basement.ethz.ch;* Vanzo *et al.* 2021). With the outputs of BASEMENT simulations, we generated inundation frequency maps. We then estimated areas prone to sediment erosion/deposition under different flow conditions. Further information on hydrodynamic modelling is given in Box 4.

2.2.3 Model linking

We linked the ecological and hydrodynamic models to realize a fine-scale prediction of suitable locations for German tamarisk seedling establishment, as this is the most vulnerable life stage, and successful establishment ensures local persistence. To predict seed dispersal and establishment, we used: (i) the adult habitat matrix from the ecological model, (ii) the inundation maps, and (iii) the erosion/deposition maps from the hydrodynamic model (Fig. 8). By multiplying probability rates for these three maps on a fine spatial scale (1 × 1 m raster as subsamples from the large raster; for details see Fig. 8), we produced probability maps that indicated the locations where German tamarisk is likely to establish as a seedling.

2.3 Case study: Moesa river

2.3.1 Site description and data collection

We tested the linked model on a small floodplain of the Moesa river, GR (Fig. 9). The reach is located near the village of Cabbiolo in an area where the river has never been channelized, but is confined by levees for flood protection. The floodplain is approximately 800 m long and the total width is between 100 and 200 m.

We monitored the site from the beginning of May to the end of September 2020. At the beginning of the study period few adult German tamarisks were present. During the study period, on 7 June and 29 August, two floods altered the river topography. We surveyed the site with a drone and digitalized the topography using Structure-from-Motion techniques (Agisoft 2020). The topography of the submerged areas was measured using handheld GPS devices.

Figure 9

Aerial image of the study site along the Moesa river, close to Cabbiolo (GR). The floodplain is confined by two lateral embankments. The white arrow represents the flow direction (from North to South) and the white rectangle represents the section of the site corresponding to the modelled results displayed in Figure 10.

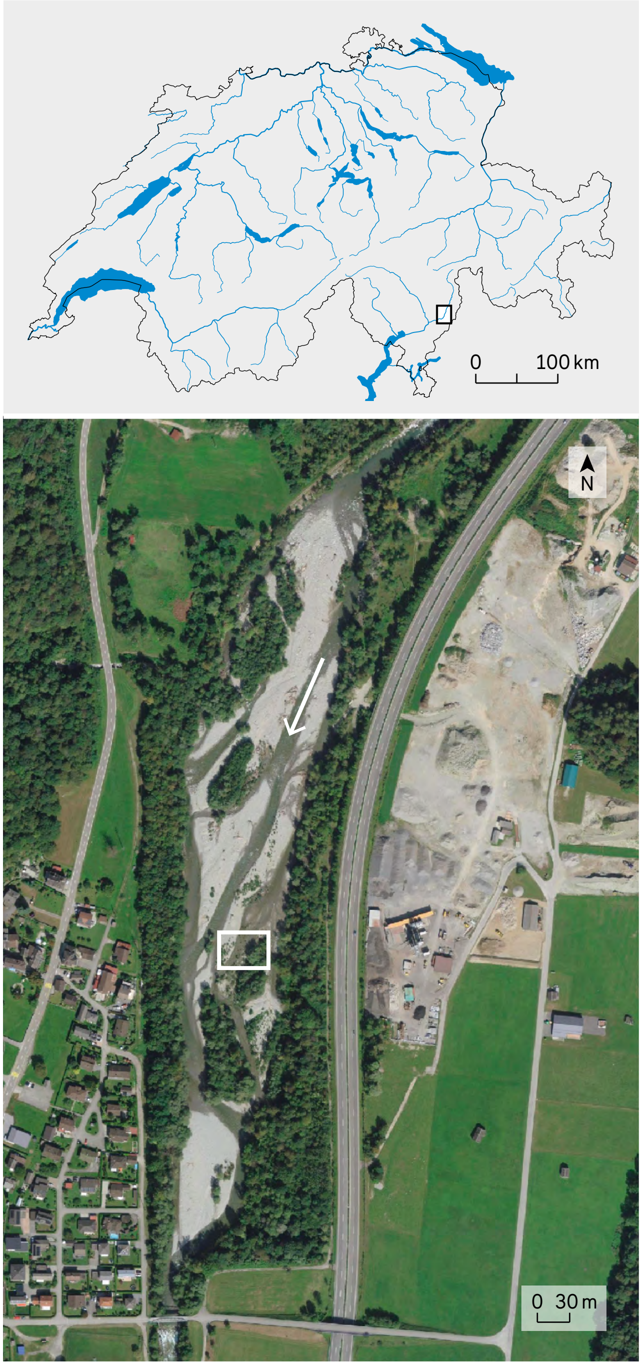


Photo: Swisstopo

The presence of German tamarisk was recorded every two weeks, covering the plant's reproductive phase from early flowering to late seed dispersal. The exact locations of the plants were measured using handheld GPS devices.

The ecological model was based on geological and climatological data for the period 1960–2016, with habitat availability modelled based on species records from the National Data and Information Center on the Swiss Flora, Infoflora (Fink *et al.* 2017; see also Chapter 1; Fink and Scheidegger 2023). The hydrological data was obtained from the Office for Nature and Environment (Amt für Natur und Umwelt) of Canton Grisons.

2.3.2 Evaluation of modelling results

For adult individuals, the level of detail of the large-scale ecological model alone was insufficient, as it did not indicate why some plants did not survive during the study period in 2020. The distribution of shrubs within the site suggests that erosion processes play an important role in determining the persistence of adult plants, but these factors were not implemented in the ecological model. Therefore, we checked if the additional information from the hydrodynamic model allowed us to predict the survival of German tamarisk.

The hydrodynamic model used discharge data from the study period and high-resolution river topography information to assess potential gravel erosion at a smaller spatial scale. Continuous erosion of gravel in early May resulted in the loss of adult plants in areas which were indeed predicted to be subject to gravel erosion and sedimentation by the hydrodynamic model. By linking the ecological model and the hydrodynamic model, the predicted habitat changes reflected the fate of the adult individuals accurately.

The linked model was mainly used to predict the locations where the successful establishment of German tamarisk seedlings is possible. While the ecological model was important for predicting the habitat of adult individuals, the inundation, erosion and sedimentation areas within the two-week periods during the flowering phase were used to predict where seed germination is likely to occur. The linked information from the ecological and hydrodynamic models made it possible to detect the general pattern of suitable seedling habitat at a small spatial scale, as established seedlings were indeed observed in some of the regions predicted by the linked model (Fig. 10).

2.3.3 Benefits of the linked model

The main benefit of the linked model is that the identification of potentially suitable areas for seed germination is possible at a finer spatial scale. Such areas are very important for the recolonization and persistence of German tamarisk. The higher accuracy of the linked model enables the prioritization of locations along the floodplain for local species promotion or targeted management actions, such as competitor (or invasive) plant removal.

The use of tools that support a high level of detail (e.g. 2D river modelling tools) and the increasing availability of high-resolution datasets from remote sensing represent a consolidated trend in practice and academia. The proposed linked model fits with this trend by exploiting the benefits of combining modelling tools with various spatial and temporal scales.

2.3.4 Limitations of the linked model

While the linked model was useful for detecting adult and seedling habitat for the target species, it involves greater modelling complexity. This is due to the difference in spatial scale (large for the ecological model and small for the hydrodynamic model) and thus the need for re-adjustment (rescaling, see Fig. 8). Additionally, the linked model does not consider all the environmental processes that a species is exposed to. The model can be further refined, for example by accounting for interactions between sediment dynamics and plants (e.g. Caponi and Siviglia 2018). Furthermore, the proposed workflow (Fig. 8) requires the use of a series of tools (e.g. BASEMENT) and some scripting skills for data elaboration (e.g. in R or Python), as it is not implemented in a single bundled tool. Nevertheless, the workflow can be fully reproduced with freeware tools.

2.3.5 Extendibility to other case studies and species

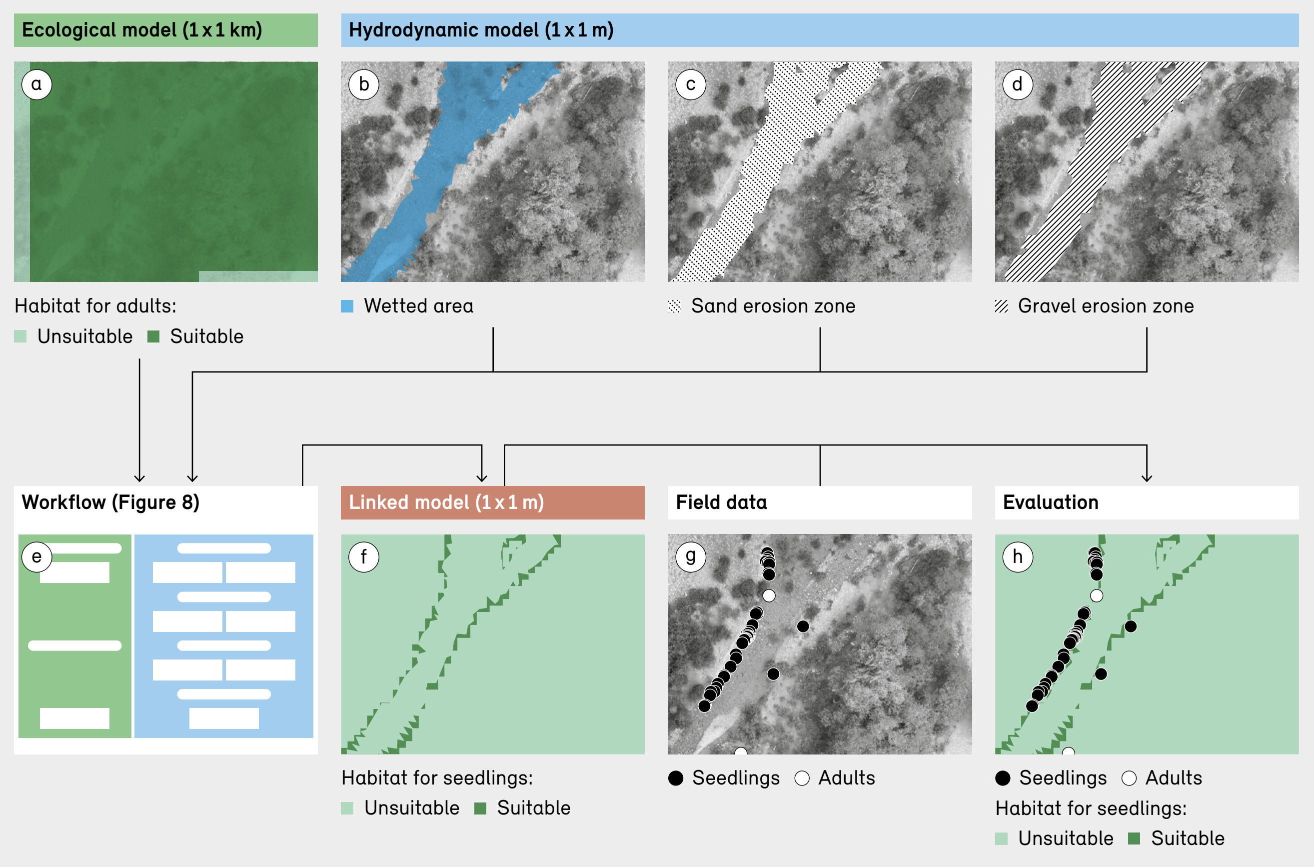
The linked model can be adapted to other river sites and other species. In particular, there are no limitations with respect to the type or size of river reach, provided that the 2D modelling approach is valid. By using BASEMENT, all types of flow conditions (i.e. both sub- and supercritical) can be reproduced; hence, both lowland and alpine reaches can be investigated.

To apply the linked model at other river sites, both the ecological model and the hydrodynamic model are required. The ecological model is executed at the national scale and available information for the German tamarisk can be used for other sites in Switzerland (Fink *et al.* 2017). The workload required for the hydrodynamic model depends on the availability of a high-quality digital terrain model (DTM), which can be time-consuming to generate from scratch. Considering the workload, we recommend using this approach in specific reaches of interest (order of kilometres) but not on a national scale.

Since the German tamarisk is an indicator species for pioneer vegetation in floodplain areas (Delarze and Gonseth 2015), the outcome presented here can also be used to infer habitat for species with similar niches (e.g. the willow *Salix daphnoides*) or non-plant species in the same habitat (e.g. the moth *Istrianis myricariella).* The methodology could also be adapted to model other types of motile species, such as fish or riparian terrestrial beetles or spiders (Box 5, see also Chapter 3; Kowarik and Robinson 2023). In this case, the ecological model step would need to be adapted to reflect the target species, and the hydrodynamic model would need to quantify the hydraulic parameters that are important for these species.

Figure 10

Evaluation of the linked model with field data on German tamarisk adults and seedlings in a section of the floodplain near Cabbiolo, GR (aerial image from winter 2020). Seedlings were present in areas identified as suitable in the ecological model (dark green area in panel a), close to the modelled inundation lines (blue area in panel b), and outside the modelled erosion and deposition zones (c: sand, d: gravel). Following the workflow to link the two models (e), the combined probability matrix (f) narrows down the locations suitable for seedling establishment (dark green areas in panels f and h) and matches the field data (g) as shown in the evaluation (h).



Source: VAW, ETH Zurich /WSL

2.4 Use in practice

The linked model is a useful tool for assessing the potential for local conservation of target species via natural rejuvenation and local growth. The red-listed German tamarisk tends to be outcompeted by more common and faster-growing willows, which render light conditions too shady for this slower-growing species. For the German tamarisk, rejuvenation along inundation lines where competition is low is crucial, and it helps this species to persist despite the co-occurrence of neophytes like the invasive summer lilac (*Buddleja davidii*; Mörz 2017). The probability map of seedling habitat facilitates the investigation of the potential for rejuvenation at sites which are impacted by hydropower. Further, it can be applied to validate restoration success by comparing the predicted habitat potential of restored areas with observations of established seedlings.

Under climate change, floods are expected to become more frequent and occur in different periods than they do currently. More accurate predictions and a deeper understanding of processes are crucial for river managers to deal with future environmental changes. With the linked model, it is possible to forecast future habitat conditions while considering changes in temperature, precipitation and discharge, leading to an improved understanding of the fate of species in a changing world.

Box 5: In practice – An application perspective on habitat modelling

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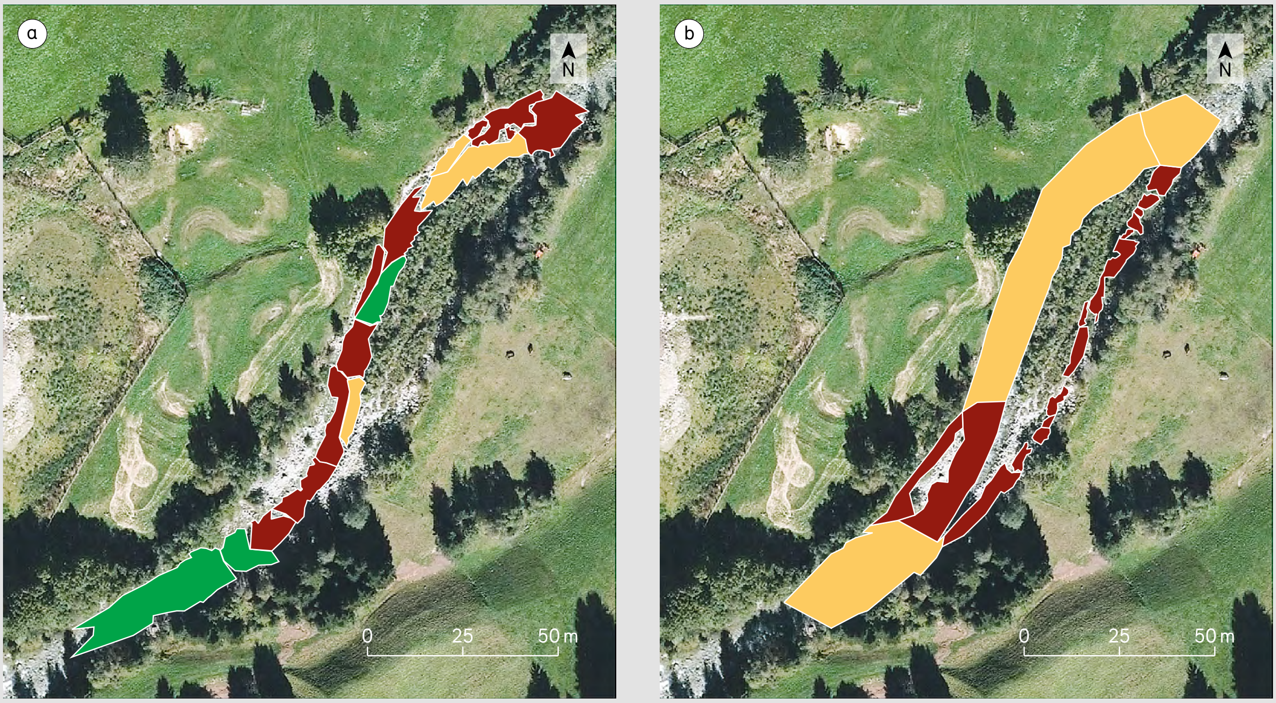
Habitat modelling can be extremely useful for assisting practitioners and decision-makers in the management of river systems. We applied habitat modelling to quantify environmental flows downstream of water abstractions for human activities (e.g. hydropower production). Minimum flows are typically defined using only hydrological relationships within the catchment, while with habitat modelling ecological aspects can be considered as well. In 2015, guidelines from the EU suggested the implementation of habitat modelling methods to define ecological flows for the Water Framework Directive.

In pilot case studies in the Italian Alps, we used the MesoHABSIM method (Parasiewicz 2011) to define environmental flows from a more ecological perspective, in line with the EU guidelines. We mapped habitat at different streamflow rates to build a habitat-discharge curve and assess habitat quality for the two main local species, the brown trout (*Salmo trutta,* Fig. 11) and the marble trout (*Salmo trutta marmoratus*). We simulated different amounts of water withdrawal for human use, and we transformed the streamflow data series into habitat series, which we used to identify the ecological flow thresholds below which habitat quality rapidly decreases. Habitat quality is assessed at the reach scale (10–1000 m) in the field, but hydrodynamic modelling can assist in extending habitat assessments to a larger spatial scale, if relevant (sub-catchment or catchment). The transformation of the streamflow data series into habitat series can also be computed at different time scales, depending on the resolution of the input data. Doing so helps us to assess the ecological effects of phenomena that might affect the river community from sub-daily (e.g. hydropeaking) to weekly or monthly (e.g. extreme droughts) scales.

The habitat modelling concept directly relates hydrology and water management to the biotic communities in rivers. In addition, this concept can be extended in order to quantify other ecosystem services, when a relationship between streamflow (or other hydraulic variables) and water use can be established. An example is the quantification of river suitability for recreational navigation (rafting, kayaking) downstream of hydropower plants under different flow conditions. Overall, the habitat modelling concept is a powerful tool for river management, and it holds huge potential for the analysis of possible trade-offs and synergies among different river uses and biotic communities.

Figure 11

Habitat suitability for adult brown trout (Salmo trutta) at river discharge rates (Q) of (a) 1.15 m³ s⁻¹ and (b) 3.95 m³ s⁻¹. Vermigliana creek, Vermiglio (IT).



Adult brown trout, Q = 1.15 $m^3 s^{-1}$

🟩 Optimal 🟨 Suitable 🟥 Unsuitable

Adult brown trout, Q = 3.95 $m^3 s^{-1}$

🟩 Optimal 🟨 Suitable 🟥 Unsuitable

Source: Courtesy of Prof. G. Zolezzi (DICAM, University of Trento, Italy)