

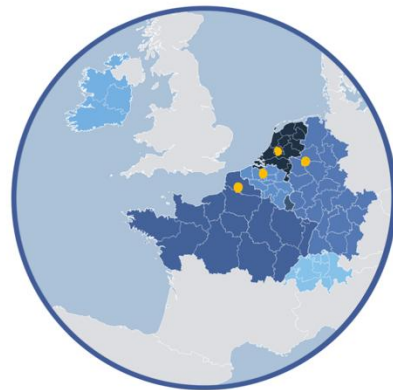
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Bonsai



A distribution model for European beaver



**Climate and
environment**

A distribution model for European beaver



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INTERREG NWE BONSAI project

Climate change

Climate change is accelerating, leading to increased rainfall, drought, storms, flooding, and sea level rise, particularly impacting the NWE region with its extensive estuarine systems. How can we better prepare these areas for climate change for the long term?

BONSAI objective

The overall objective of BONSAI is to make flood defence systems in tidal estuaries of NWE more short and long term resilient against climate change by learning from sites in different climate zones over Europe and developing and sharing pro-active and responsive measures. Organisations responsible for flood resilience and societal partners in tidal estuaries in NWE are empowered through capacity building to strengthen their resilience and better act in case of flood threats caused by extreme weather events.

Main results

The main results are (1) a transnational strategy for national authorities and 3 action plans for regional and local authorities, (2) 5 solutions on increasing robustness and resilience and enhancing disaster management and (3) multiple training schemes and courses on flood disaster management and flood resilience and 1 joint transnational flood academy.

BONSAI aims

BONSAI aims to apply a holistic approach that is focusing on (short and long term) flood defence system resilience and the improved disaster management. Different NWE countries tackle these challenges from their own perspective. Transnational cooperation between the NWE regions and beyond is essential because estuarine systems and climate change transcend borders, offering opportunities for mutual learning and resilience building.

Unique approach

The BONSAI approach is unique, 1. bridging the three layers of the multi-layer water safety approach: prevention, disaster management, and spatial planning 2. simulating shifting climate zones based on the application of insights from more southern regions to northern regions and 3. focusing on increased cooperation between countries to learn from each other, north learning from south as well as south learning from north.

1 Introduction

Earthen levees are a critical component of flood protection in Northwestern European estuarine systems, safeguarding large populations and major economic assets. As predominantly green structures, these levees naturally attract burrowing animals such as moles, foxes, rabbits, badgers, and, increasingly, beavers (Tsimopoulou, 2026). Within a comprehensive risk analysis framework, several sequential steps determine whether beaver burrowing behaviour will escalate into critical structural damage (Figure 1). The first three steps of this framework assess the probability of a beaver burrowing into a risk-sensitive levee: first, suitable habitat must be present for a population to settle; second, beavers must be able to navigate to and access the site; and third, they must have direct physical access to the levee to begin digging. This report establishes a methodology specifically designed to identify and evaluate the first two steps of this framework (Figure 1).

The Flemish Research Institute for Nature and Forest (INBO) developed a model to predict the potential spread of beaver in a given region over a period of three years (Huysentruyt & Rutten, 2021; 2024; Huysentruyt et al., 2025). This model combines a habitat suitability analysis with a dispersion model, both based on the known distribution of beavers in a given region. In this report we summarize the methodology used in this analysis. The report does not describe the development of this model (model building, model calibration and model validation). These steps can be found in Huysentruyt & Rutten (2021; 2024).

This report is conceived as a general guidance document but uses the situation in Flanders in 2025 as an example.

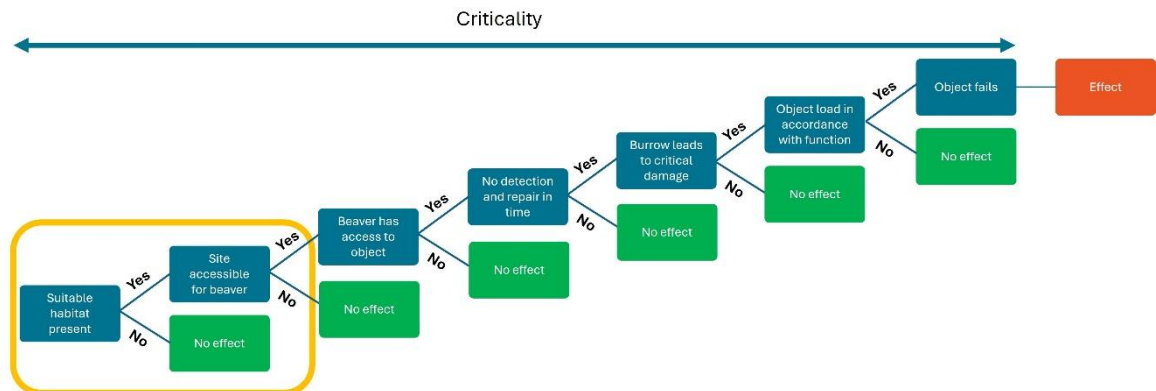


Figure 1: Overview of the different steps in the risk assessment for beaver burrowing damage (modified from Stellingwerff, 2026). The orange square indicates which steps this model contributes to.

2 Material and methods

2.1 Distribution data

To determine the potential spread of beavers in a given area, the basic data needed is the current distribution of beavers in that area. For this, we use the spread of territories across Flanders, as determined by clustering beaver observation data (tracks, burrows,...) from different sources (Huysentruyt 2026). This distribution is used in two different ways. First, this data is used to determine habitat preferences of beavers within that area. By comparing presence versus absences of beavers with different habitat characteristics, a map of suitable habitat can be created. Second, the current distribution is used as starting points to model potential dispersion of beavers through the landscape, where habitat suitability is used to calculate landscape resistance.

The distributions used in this example are the 2024 distribution to determine habitat suitability and subsequently the 2025 distribution as dispersion starting points. This source data can be downloaded through [10.5281/zenodo.20407654](https://doi.org/10.5281/zenodo.20407654), where all beaver territories in Flanders from 2023-2025 are listed (Huysentruyt 2026).

2.2 Habitat suitability model

To map suitable habitat, we used beaver territories in Flanders in 2024, where we calculated the 95 % Minimum Convex Polygon as the current distribution in which we could compare presences versus absences of beaver. For the species distribution model, we used the *MaxEnt* algorithm (Phillips et al., 2006; Phillips & Dudík, 2008; Merow et al., 2013; Phillips, 2017). Evaluation of model parameters was done using the *ENMeval* R-package version 0.3.1 (Muscarella et al., 2014). For model building we used the R-package *dismo* version 1.1-4 (Hijmans et al., 2017).

For the background habitat characteristics, we used the most recent version of the biological valuation map (BWK) within Flanders (De Saeger et al., 2023). This map is an area-wide inventory of the biological environment and soil cover within Flanders. We combined information from this map with data on watercourses and water bodies available in the Large Scale Reference Dataset (AIV, 2018). Since beavers prefer wider streams over narrower ones (Müller-Schwarze & Sun, 2003), we only selected tidal estuaries and navigable streams, streams with a catchment area of over 5000 ha, and streams that had a catchment area of over 100 ha which also crossed municipality borders. In the Flemish legislation, these stream types are respectively labelled as categories 0, 1 and 2, a categorization also used in the official geographical base map for Flanders (AIV, 2018). As most foraging activity of beavers occurs within 40 m from water (Belovsky, 1984), we further limited accessible habitat to a buffer of 50 m around the selected streams and around water bodies with a minimum surface of 1000 m², located within 500 m of the forementioned watercourses. The availability of habitat evaluated this way was thus limited to this buffer within the distribution polygon. This zone represents all locations accessible to beavers. Within this zone, the composition of available habitat was limited to eight different types, in analogy with the model of Swinnen (2015):

- grasslands
- swamps
- thickets
- willow scrub and swamp forest

- poplar forest
- other deciduous forest
- water bodies
- other potential habitat (hedges, parks,...)

All other habitat types, anthropogenic land use but also including natural areas that were deemed to be unfit for beavers (like heathland, dunes,...) were excluded from the analysis.

To allow our model for beavers to move in and out of Flanders, we selected a 10 km buffer around Flanders. Since BWK-data is limited to Flanders, for this analysis, we selected 9 landscape variables from the European Land Cover mapping on the 10 m scale (ELC10) (Venter & Sydenham, 2021):

- lichens and mosses
- shrubs
- periodically herbaceous
- permanently herbaceous
- deciduous trees
- evergreen trees
- coniferous trees
- poplar
- willow

Again, we select only available habitat around water courses, similar to the approach within Flanders. For this purpose, we selected all water courses from the EU-Hydro River Network Database (EU-Hydro) within Flanders and the 10 km buffer (EEA, 2021). This has a lower resolution than the approach using waterway categories in Flanders, but was the only layer available that was standardized for both Flanders and the surrounding regions.

Since the model based on ELC10 data performed less than the model based on BWK data, we combined the output of both models to develop a habitat suitability map for the entire region. Within Flanders, we used the output based on BWK data, output based on ELC10 data was used within the 10 km buffer.

2.3 Dispersion model

The presence of suitable habitat does not automatically imply the expected presence of beavers. To determine this, the probability of beavers dispersing into a specific habitat patch must be taken into account. To do this, we constructed a dispersion model that combines population growth with the current distribution of beavers, the location of suitable habitat patches and the accessibility of these patches via waterways. This way, we can estimate the probability of beavers settling at a given location within a set time frame.

To model movement of beavers through the landscape, we used the R-package *SiMRiv* version 1.0.4 (Quaglietta & Porto, 2019). Output was visualized using the R-package *leaflet* version 2.0.3 (Cheng et al., 2019).

It is important to note that this model predicts the spread of beaver territories rather than individual animals. Each successful settlement in a new location is defined as a new territory, which then serves as a potential starting point for further dispersal in the following year. While this approach relies on a few assumptions that deviate from biological reality, the model's purpose is not to precisely forecast future

population dynamics, but rather to assess the probability of a location becoming occupied. Because this information is designed for use within a spatial risk assessment framework, the model has been deliberately calibrated to minimise false-negative predictions, even though this results in a higher probability of false-positive predictions.

The initial number of dispersing beavers was set to the number of established territories in the starting year. To account for population growth, this baseline was multiplied by 1.21 each year, reflecting the observed annual population growth rate in Flanders from 2014 to 2019.

To simulate beaver movement across the landscape, the model requires data on landscape permeability, allowing a simulated dispersing individual to follow the path of least resistance through suitable habitats and watercourses. In the *SiMRiv* R package (Porto & Quaglietta, 2019), this is operationalized as landscape resistance (or impermeability). Resistance was incorporated via two mechanisms:

- Habitat Inversion: Habitat suitability scores were inverted to represent landscape resistance.
- Corridors of Least Resistance: Large waterways (categories 0 and 1) were integrated as potential dispersal routes with zero resistance in both directions, regardless of direction of flow.

To invert habitat suitability into resistance, we adapted the formula by Carroll et al. (2020), introducing a slight non-linear deviation from a strictly linear relationship:

$$w = \frac{(100 - 99 * \frac{(1 - e^{-1*h})}{1 - e^{-1}})}{100}$$

Where w is resistance and h is the measure for habitat quality.

Landscape resistance values were calculated per square kilometer and coupled to large waterways using the *resistanceFromShape* function in the *SiMRiv* package. A 200 m buffer was applied around these waterways to ensure simulated beaver paths would intersect with and follow the watercourses. This value, along with other parameters used in this model as described below, were obtained through a model calibration and validation process using known distributions of beaver in Flanders in the period 2003-2017.

Dispersal movement was simulated using a Lévy Walk (LW) model via *SiMRiv*, which alternates between local, uncorrelated random steps (Random Walk, RW) and highly directional steps (Correlated Random Walk, CRW) (Porto & Quaglietta, 2019). We set a step length of 40 m, a perceptual horizon of 1 km, and a CRW directional correlation of 0.98. The probability of switching between RW and CRW states was kept low (0.1), allowing dispersing individuals to cover long distances while resident individuals remained localized.

For each simulation, a beaver executed 60,000 LW steps from a random starting point to reach an endpoint. Settlement success at the endpoint was determined by a binomial distribution based on local habitat suitability (e.g. an 80 % settlement probability in a habitat suitability of 0.8). Successful settlements established new territories. If a settlement failed, up to three total attempts were made from the same starting point. Following a successful settlement, the habitat suitability of that square kilometer was reduced by 0.1 to discourage multiple settlements in poorer habitats. This adjustment did not alter landscape permeability, as beavers can freely traverse occupied territories but are less likely to settle in them.

The source code of this model can be downloaded at [10.5281/zenodo.17406546](https://zenodo.org/record/17406546/files/10.5281/zenodo.17406546).

3 Results

A total of 20 model runs yielded 35,963 endpoints from simulated dispersal events, distributed across 8,145 square-kilometer cells in Flanders. Based on the frequency of endpoints per square kilometer, occupancy probability was categorized into four classes:

- Incidental: 1 endpoint
- Low: 2-4 endpoints
- Medium: 5-8 endpoints
- High: >8 endpoints

However, this initial occupancy probability does not account for the actual spatial extent of a beaver territory. Consequently, some square-kilometer cells might not be designated as potentially occupied despite being entirely surrounded by occupied cells. To account for this edge effect, the scale of predicted occupancy was expanded to include all adjacent cells (a 9 km² focal window). Whenever the average value of the surrounding cells exceeded the value of the central cell, the central cell's value was adjusted upward. This focal smoothing effectively filled artificial gaps in the spatial distribution of occupancy probability.

To estimate final occupancy probability, the four occupancy classes were cross-referenced and reclassified against the underlying habitat suitability (as shown in Table 1). This resulted in 3,264 km² cells classified as low occupancy probability, 1,764 as medium, and 2,319 as high (Table 1, Figure 2).

Table 1: Distribution of reclassified occupancy probability in 2028 over all kilometer square cells in Flanders, based on initial occupancy probability and underlying habitat suitability (white: none, light blue: low, blue: medium and dark blue: high).

Initial occupancy probability	Habitat suitability				Total
	0-0.25	0.25-0.5	0.5-0.75	0.75-1	
None	1,527	1,868	395	8	3,789
Incidental	1,096	2,102	498	18	3,714
Low	377	2,371	1,063	40	3,851
Medium	27	634	1,178	111	1,950
High	0	39	658	333	1,030
Total	3,027	7,014	3,792	510	

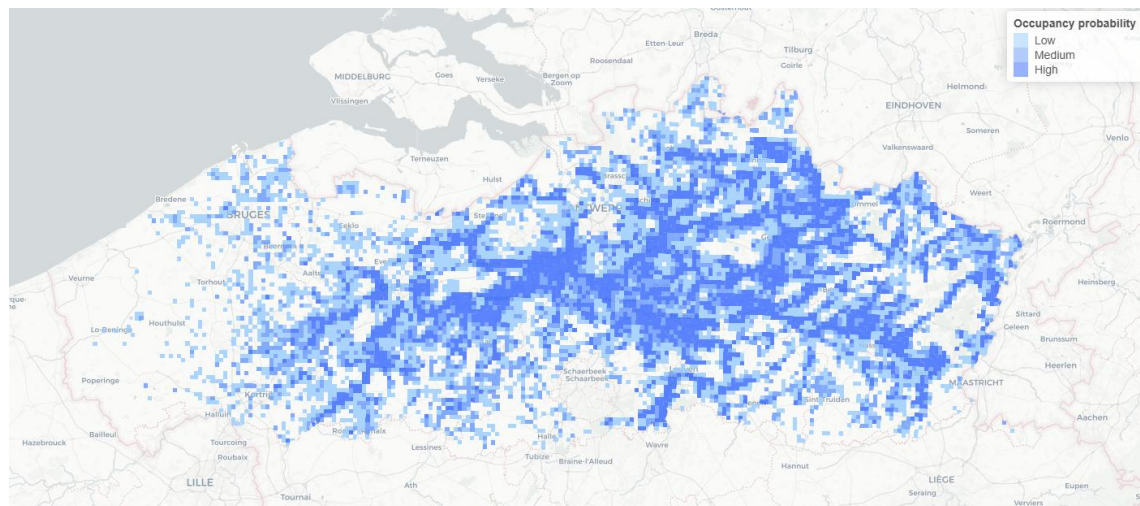


Figure 2: Predicted spatial distribution of occupancy probability of beaver in Flanders in 2028.

4 Discussion

Originally validated by Huysentruyt & Rutten (2024), the model was subsequently updated and expanded by Huysentruyt et al. (2025). While these recent adjustments significantly enhanced the model's performance, it still tends to overestimate occupancy probability. Consequently, when interpreted in its broadest sense, the model can become less informative. Conversely, it is highly effective at identifying zones where beavers are unlikely to settle in the near future. The model is primarily intended for strategic screening at regional scales (e.g. province, river basin or municipality) rather than site-specific management decisions.

Because the model relies on fixed thresholds to classify occupancy probability and operates strictly on a three-year temporal scale, its predictions remain indicative rather than definitive. It should not be used as a strict zonation tool to declare absolute beaver presence or absence.

Instead, these broad-scale outputs are best utilized as an initial screening mechanism within a larger risk analysis framework. By identifying where beavers are most likely to settle, managers can narrow their focus to high-probability zones. Within these targeted areas, practitioners can then deploy subsequent, fine-scale assessments to evaluate specific hazards, such as digging, object failure, or property damage.

While our model predicts multi-year spatial occupancy by combining habitat suitability with landscape permeability, it serves a distinct yet complementary function to other recent models in the region. For instance, the agent-based model (ABM) by van den Berg & Noyons (2024) focuses on micro-scale individual decision-making under acute abiotic stress (like high-water events). Conversely, Warmer et al. (2025) evaluate macro-scale metapopulation viability and national risk zoning across infrastructure networks. In the context of a comprehensive levee risk assessment framework, our model effectively functions as an initial screening tool (steps 1 and 2, Figure 1), establishing high-probability zones where fine-scale behavioral models like van den Berg & Noyons' can subsequently assess localized digging hazards (step 3 (&4), Figure 1).

To further increase the applicability of this model, future research should focus on model integration into a nested framework. This way, outputs from this regional model could feed directly into micro-scale agent-based models to evaluate localized digging hazards at specific levees. Also, improving the resolution and cross-border compatibility of land cover datasets beyond Flanders would enhance model performance in border regions where lower-resolution substitutes currently reduce model accuracy.

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