Beaver digging during highwater with an agent based model

Case studies in Dutch river sections

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Abstract

Since the reintroduction of the beaver in the Netherlands in 1988, its population has grown exponentially and poses a safety problem for the levees because:

- The safety of the levees can be (seriously) endangered by burrowing in the levee, all the more so since beavers tend to dig new burrows when high-water is developing.
- The beaver burrow is exceedingly difficult to detect, because its entrance is below the water level and then remains too deep below the surface to be discovered with conventional detection methods.
- The beaver is protected under the EU Habitat Directive and plays a key role in improving biodiversity in flora and fauna. Generally, it may not be killed, and its habitat may not be modified.

In this report an improved model of the behaviour of beavers during high-water is presented with an Agent-Based Model (ABM). The inputs of this model are based on an extensive overview of parameters that influence beaver behaviour, which is based on literature and consultation with beaver experts. When comparing the model result with field observations, the model appears to be able to predict the locations of the beaver burrows with acceptable accuracy, but it is not yet very sensitive to hydro-meteorological conditions. The validation data is not very comprehensive, hence a challenge remains in differentiating between hydro-meteorological conditions at the burrow locations and their time of detection. A more complete set of data would greatly improve calibration effectiveness and advance the model even more. It is always necessary to run the model various times on the same settings to account for randomness of hydro-meteorological sensitivity, lodge location (beaver's home), and burrow location selection. The more information about the territory is available, such as lodge locations and number of beavers in the river section, the more accurate the prediction will be. Nevertheless, it is important to note that there is still much uncertainty related to beaver behaviour and the extent to which it can be modelled.

The results of this research study will be used to estimate the probability of levee failure given animal burrows. This model can also be used to discover patterns of where beavers will possibly dig during a high-water event, so dike inspectors can prioritize those locations.

For further development of the model the following recommendations and proposed extensions are important:

- Including river flow velocity in the model.
- To obtain a better calibration of the model it is necessary to obtain more and more detailed data and have more insight in beaver behaviour. To facilitate the process of obtaining accurate data for calibration, a detailed questionnaire has to be prepared, and dike inspectors or other observers should be trained for filling out these questionnaires correctly. During high water situations there is not always time for this, but in that case an estimate afterwards is better than no information.
- Comparing observations with model results will further validate the model and help to find the key aspects and parameters that result in sound predictions (Grimm & Railsback, 2012).
- Publishing the model on Netlogo Modelling Commons, an online platform for open-source ABM. In a later stage, after calibration is finished, the model could be integrated into a dashboard, for an easy user experience, since the model was created with the intention to be shared with professionals in the field such as dike inspectors of water authorities.

Contents

1 Introduction

1.1 Problem statement

Animal burrowing in levees is a phenomenon that has been dealt with for years in The Netherlands and abroad to prevent failure of the levee. This task is being carried out expeditiously by the Water Authorities. Since the reintroduction of the beaver in the Netherlands in 1988, its population has grown exponentially and poses a safety issue for the levees because:

1. The safety against flooding of the levee can be (seriously) endangered by burrowing.
2. During high-water periods beavers will search for higher places near the river to dig a burrow, in many cases choosing a levee as a refuge location.
3. The beaver burrow is extremely difficult to detect, because its entrance is below the water level and then remains submerged to such an extent that it can hardly be discovered with conventional detection methods.
4. The beaver is protected by the EU Habitat Directive and plays a key role in improving biodiversity in flora and fauna (Nica et al, 2022). In general, it is not allowed to kill or disturb a beaver, nor is it allowed to deteriorate its habitat.

Especially during high-water, beaver burrows in the levee are a major risk because then beavers tend to dig into the levee to create a new burrow, which in many cases has a negative effect on the strength of the levee. Thus, animal burrows in flood defences such as levees can, depending on location, type of animal, and other factors, increase flood risk substantially.

1.2 Aim of the study

In 2023 first steps have been taken to develop an agent based model (ABM) trying to understand the behaviour of beavers during high water (Van den Berg & Natarajan, 2023).

In this report the behaviour of beavers during a high-water period in The Netherlands is simulated with an Agent-Based Model (ABM) to investigate whether and where they dig. The model is derived by extensions in a previous version of the model (Van den Berg & Natarajan, 2023) by adding geographical information and updated parameters. Any area in The Netherlands can be selected from a GIS dataset and then analysed with this new model. The model predicts beaver behaviour in various conditions for a specific part of the river and its surrounding levees. The results are patterns in beaver behaviour during high-water by which management recommendations for water authorities can be given and dike inspectors can be guided to potential danger areas during high-water events. It also provides quantitative input for a risk assessment with a developed safety framework of animal burrows in levees.

2 Behaviour of the beaver

2.1 Aspects which play a role in the behaviour of the beaver

Based upon different discussions with Daan Bos (Van Hall Larenstein) Vilmar Dijkstra and Wesley Overman (both from the Dutch Mammal Society) and Literature review (Nitsche, 2000) and (Nitsche, 2003) a list of all the factors/parameters that may play a role as a result of which the beaver digs into a flood defence at high water has been drawn up. See Table 2.1. In this table the different factors parameters are described as well as whether they play an important role in the behaviour of the beaver to decide when it wants to dig or not during high water.

Table 2.1 Factors/parameters that may play a role as a result of which the beaver decides to dig into a flood defence at high water.

#	Parameter	Normal situation (N)/ High water situation (HW)	Explanation	Indicator	Used in model	Group*	Plays an important role
1	Availability of alternative resting place	HW	The quality of an alternative resting place is very important. E.g. is it high enough, are there other animals in the vicinity, are there other places inwards, availability of waterways inward? Alternative resting places have to be stable for a long period	Number/ km^2	Yes	E&W	++
2	Air tempera-ture	HW	This plays an important role for young beavers because their temperature regulation is not yet well developed. The bigger the animal, the less effect the air temperature has on them. When the beaver is in a burrow it will use less energy.	° Celsius	Yes, as a boundary condition	E&W	++
3	Wind direction & - speed	HW	During high-water, the beaver will look for places in the lee to shelter or to dig. Also, windchill plays a big role (see air temperature).	Orientation/ km/h	Yes, as a boundary condition	E&W	++
4	Duration high water situation	HW	The longer the high-water situation lasts, the higher the probability that a beaver starts digging a burrow in a levee.	Hours	Yes	E&W	++
5	Experience with previous high water	HW	There seems to be a correlation, but it is difficult to model. There is also an assumed correlation with age.	-	-	A, C & B	+

#	Parameter	Normal situation (N)/ High water situation (HW)	Explanation	Indicator	Used in model	Group*	Plays an important role
6	Precipi-tation (rain/hail/snow)	HW	Precipitation during the winter period can cause the beaver to seek shelter earlier and, if possible, to dig into a levee. There is also a relationship with the temperature and the duration and height of the high-water.	mm/ week	Yes, as a boundary condition	E&W	+
7	Kind of vegetation	N HW	The beaver likes to seek protection around the place where he digs. So, the beaver will often dig his burrow on a location where there is a lot of vegetation. This protects him and is also a source of food. Especially vegetation like roots, trees, certain plants and thicket. With little vegetation around, there is less probability of digging.	-	Yes, proximity to woody vegetation	E&W	+
8	Availability of driftwood:	HW	In the aftermath of the highwater of December 2023 in the Netherlands, when the river levels dropped, several beaver burrows were found underneath driftwood, see for example Figure 2.1. As mentioned, this is also gives them a feeling of safety.	-	-	E&W	+
9	Age Beaver	HW	The age of a beaver plays an important role. It is assumed that younger beavers are more likely to seek a hiding place and therefore possibly dig into a levee than older beavers.	years (average 7-8, max 15)	Yes, as boundary condition. Super individual (family based as a group)	A, C & B	+
10	Relation to other agents nearby	HW	In this case other agents are beavers. This is one of the factors which can be investigated with earmarked beavers. Scent marks on the slopes play an important role. If the other agents are no family, there will be a very hostile reaction from both sides. Other agents can also be other animals, predators or even boats.	friendly, hostile, neutral, fled, etc	-	A, C & B	+/-

#	Parameter	Normal situation (N)/ High water situation (HW)	Explanation	Indicator	Used in model	Group*	Plays an important role
11	Steepness slope of the levee	N HW	In case of a mild slope on the water side of the levee, the beaver has to dig further to reach a dry place. This could be an important aspect for a high-water refuge design for beavers.	%	-	E&W	+

*) Group E & W = Environment & weather conditions
Group A, C & B = Attributes, capabilities, and behaviors of the agents in the model

Also, some additional aspects have been indicated, but at this moment it is uncertain if these aspects play an important role. These additional aspects are: Social status, family size, origin/experience in this territory, moving out of offspring, natural enemies, protected status, sex of the beaver, moment in the season, water depth of the ditch, water temperature, obstructions (i.e. revetment, netting, riprap, etc..) and material of the levee.

Figure 2.1 Discovered beaver burrow under driftwood after the high-water recede in December 2023 at Waterschap Rivierenland (source Waterschap Rivierenland).

3 Methods

3.1 Introduction

This research expands on a previous study to model beaver behaviour during high-water using Agent-Based Model (ABM) software NetLogo 6.3.0. An extensive overview on this study and the background of ABM is available in (Van den Berg & Natarajan, 2023).
The version of the model in current research includes an extended set of parameters and expanded sub-models. It also includes Dutch GIS data and is illustrated by two case studies for Dutch river sections.

3.2 GIS data processing

Model boundary conditions such as the spatial extent of the study area, the elevation and the location of vegetation can be derived from spatial datasets and included in the model as such. In The Netherlands these data can be openly accessed and downloaded through PDOK[1] from the BGT[2] and AHN databases[3]. Both datasets offer a download viewer in which the desired area to be downloaded can be selected on a map.
NetLogo works with limited spatial data formats, so before importing the GIS data into the model, they have to be processed. This can be done in QGIS, an open-source software for spatial data and analysis.
Firstly, the coordinate reference system must be adjusted to be compatible with NetLogo, which is done by reprojecting the data from EPSG:28992 (Amersfoort RD New) to EPSG:4326 (WGS 84). This is done for both the elevation raster and the BGT shapefiles.
As not to import irrelevant data into NetLogo, the BGT dataset is filtered to only include the following land use types: levees, water bodies, shrubs and trees. These types are saved separately as shapefiles. The elevation raster is converted to an ascii file. To make the model easily usable for various study areas in The Netherlands, the GIS processing was automated in a QGIS model also shown in the same appendix.
The water authority 'Waterschap Drents Overijsselse Delta' (WDOD) shared a dataset of 184 beaver burrow observations that were made in their administrative area between January 2020 and May 2024.

3.3 Model overview

3.3.1 Purpose

The purpose of this model is to build upon the previous version of the model, by introducing geographical information and updated parameters. Any study area in The Netherlands can be selected and analysed in this new model, to represent beaver behaviour in various conditions within a specific part of the river and its surrounding levees. This gives the opportunity to

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[1] PDOK is a Dutch open-source geodata platform which offers government datasets as webservices and download services. Accessible through https://www.pdok.nl/

[2] Basisregistratie Grootschalige Topografie (BGT) is the Dutch registration of all large scale topography such as buildings, roads, water, train tracks and nature areas. It is kept up to date by local government and has a spatial accuracy of 20 m. https://bgtviewer.nl/info/over-de-bgt

[3] AHN is the Dutch national digital elevation model. The data is collected by aerial laser scanning techniques and updated every few years by governmental organizations and has a spatial accuracy of 0,5 m. More information is available at https://www.ahn.nl/ and data is downloadable at https://service.pdok.nl/rws/ahn/atom/index.xml

discover patterns in beaver behaviour during high water, provide recommendations for water authorities and guide levee inspectors to potential danger areas.

3.3.2 Entities, state variables and scales

The model has two entities:

1. Agents: representing beaver families and their competitors.
2. Patch cells: grid cells that represent the world in which the agents act. In this case these cells are based on raster cells from a digital elevation model (DEM) and landscape features.

Each agent is characterized by state variables: identification number, energy, decision to dig, target patch, safe place, high water duration sensitivity, temperature sensitivity and result. Patch cells are described by their location, elevation, patch-type and proximity to trees. The state variables are dependent on global parameters, of which many are inputs in the model. They include windchill, level of high water, duration of high water, precipitation, wind direction, initial number of beavers, number of competitors, initial energy level and radius of competitor avoidance. These parameters can be adjusted by the user in the interface tab of the model.
The different variables are expanded upon in Table 3.1 and the parameters in Table 3.2.

Table 3.1 State variables and parameters, measure.

Entity	State variable	Measure	Explanation
Beaver family	Identification number	Number	Unique identity number for each beaver
	Energy	Likert-scale	How tired/anxious is the beaver?
	Initial decision	To Dig/Not to Dig	Decision on whether to dig or not to dig based on the combination of parameters and duration sensitivity and temperature sensitivity.
	Safe place	Patch number	The target choice of hiding place
	Success?	Yes/no	Calculated based on the final safe place and the decision to dig .
	Radius-avoidance	Nr of patches	Radius within which the beaver must avoid other beavers and competitors at all times
	Duration sensitivity	Number	Number of days of high water before the beaver starts to dig.
	Temperature sensitivity	Degrees	Temperature below which a beaver starts to dig.
	Dug	Yes/No	Did the beaver dig?
Patches	Elevation	Meter	Elevation of each patch of river
	Location	X,Y	Location of each patch of river
	Patch-type	River, Flood, Levee, Floodplain, Trees, Shrubs, Urban, Water, Lodge	Landscape features
	Near-trees	True/false	Proximity of <15 m to vegetation
	Near-water	True/false	Proximity of <20 m to water
	Cover	True/false	Whether or not the patch is protected from cold wind by the side of a levee. Depends on wind direction.

Entity	State variable	Measure	Explanation
	Floodable	True/false	Whether the patch is located inside or outside the levees.
Competitors	Identification number	Number	Unique identity number for each competitor
	Energy	Likert-scale	How tired/anxious is the beaver?
	Decision to dig?	Yes/no	Decision on whether to dig or not to dig based on the combination of parameters
	Safe place	Patch number	The target choice of hiding place
	Success?	Yes/no	Calculated based on the final safe place and the decision to dig .

Table 3.2 Input parameters used in the model.

Parameter	Unit	Description	Range
Water-level	Meter	Water level of the flood (or high water) in the model	0 - 15 m
Water-duration	No of days	Duration of the high water period	0 – 10 days
Windchill	Celsius	Temperature experienced by the beavers in the study area	10 to -10
Wind-direction	Select option	Direction of the wind in the study area	N, NW, W, SW, S, SE, E, NE
Precipitation	Boolean	Precipitation in the study area. Can be switched on or off.	Yes/No
No of beavers	Nr	Initial number of beaver families that the model will run with	0 – 20
Energy	Likert scale	Initial amount of energy that the beaver and competition start with (in terms of points). Also referred to as fed-upness	0 – 3000
No of competitors	Nr	Initial number of competitors that the model will run with	4 (default, can be reset with no limit on number)
Flow-direction	Select option	Main direction of the river flow in the model. Based on this, the competitors can be initialized on the right locations as well as the model world shape.	Horizontal/Vertical
Random-lodges	Boolean	Randomly places a given amount of lodges in the model. Have to be on floodplains, near water, near trees.	Yes/No
Nr-of-lodges	Nr	Amount of lodges to place if random-lodges = true.	1-5

3.3.3 Process overview and scheduling

Similarly to the previous version of the model, there are multiple procedures performed by the beaver families and competitors. The parameters and conditions of these procedures, which model the agent behavior, have been further developed following consultation beaver experts Wesley Overman and Vilmar Dijkstra from the Dutch Mammal Society (Zoogdierenvereniging) and literature. An updated conceptual model is shown in Figure 3.1.

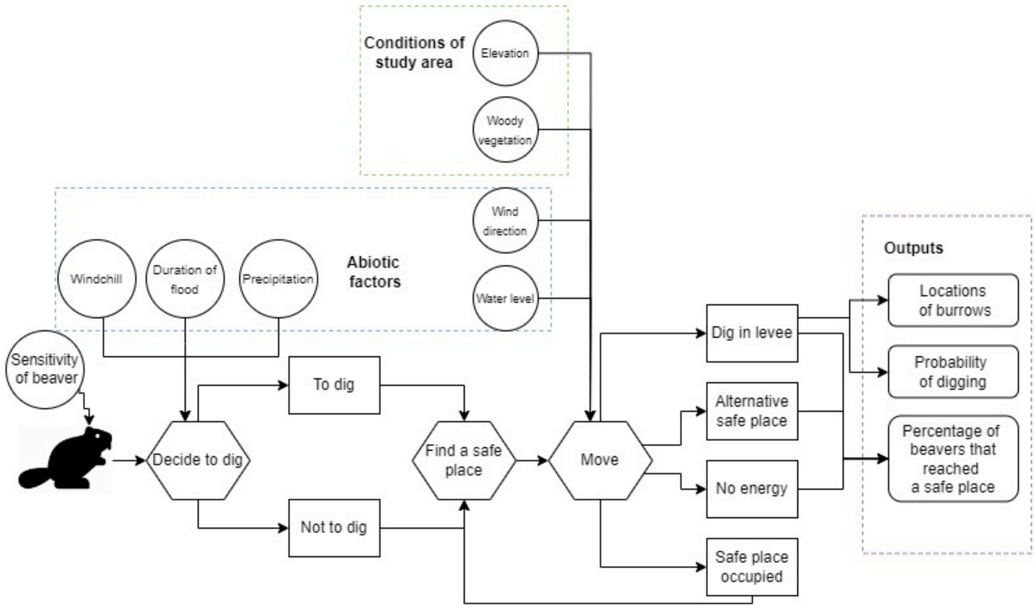

Figure 3.1 Conceptual diagram showing the overview of processes in the model.

3.3.4 Initialization

The modeled world is highly based on physical aspects of the study area in this version of the model. The size of the study area is adaptable to the study area in the real world. E.g. the Dodewaard case covers a section of a river of about 3 km (see Case Dodewaard). The Harculo case is a section of about 5 km (see Case Harculo). Based on the digital elevation map (DEM) and landscape features imported with the GIS extension, elevation values are attributed to the patches and patch types are assigned. Instead of letting the beavers start from a random point in the model as done in the former research study, they are initialized on pre-defined lodge locations. If lodge locations are unknown, there is an option to place them randomly on a floodplain patch close to the river. Competitors start from random locations on both sides of the model, only on floodplains. Where elevation in the DEM = 0, patches are classified as “river”.

Both the beavers and competitors have an initial energy level that is adjustable. Since the size of the study area is quite big and the energy variable is linked to the distance the agents can travel, the initial energy is increased significantly compared to the previous version and now has a maximum value of 3000 instead of 60 in the former research study. To deal with the assumption that not every beaver has the same sensitivity to cold temperatures or flood duration, the variables duration-sens and temp-sens were added. These sensitivity variables rely on a randomly picked value within a normal distribution above or below which they decide to start digging. To reduce the randomness, and assuming that a beaver or competitor is likely to be sensitive to both cold and long floods, meaning ‘weaker’ and ‘stronger’ beavers, the temp-sens is based on the duration-sens following the equation:

$$temperature\ sensitivity = -1.5 * (duration\ sensitivity) + 5\ .$$

In Figure 3.2 the probability density of flood duration sensitivity and temperature sensitivity of beavers and competitors are shown. Note that with a low initial number of beavers (the default is 10), it is important to run the model at least 50 times to ensure a normal distribution.

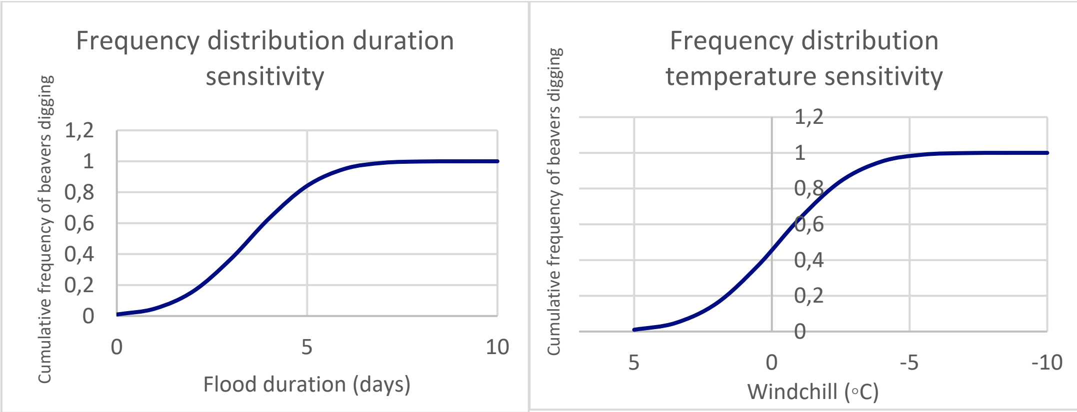

Figure 3.2 Probability density of flood duration sensitivity and temperature sensitivity of beavers and competitors.

3.3.5 Input data

The input parameters as described in Table 2.2 are adjustable within realistic ranges to simulate specific high-water situations in the past or future. In Netlogo, the model interface with input spaces looks like Figure 3.3. When running in batch, the model tool BehaviorSpace is used which is located under the Tools tab. Alternatively, the model can be run in a Python interface, using the PyNetLogo library that links NetLogo to Python (Jaxa-Rozen & Kwakkel, 2018).

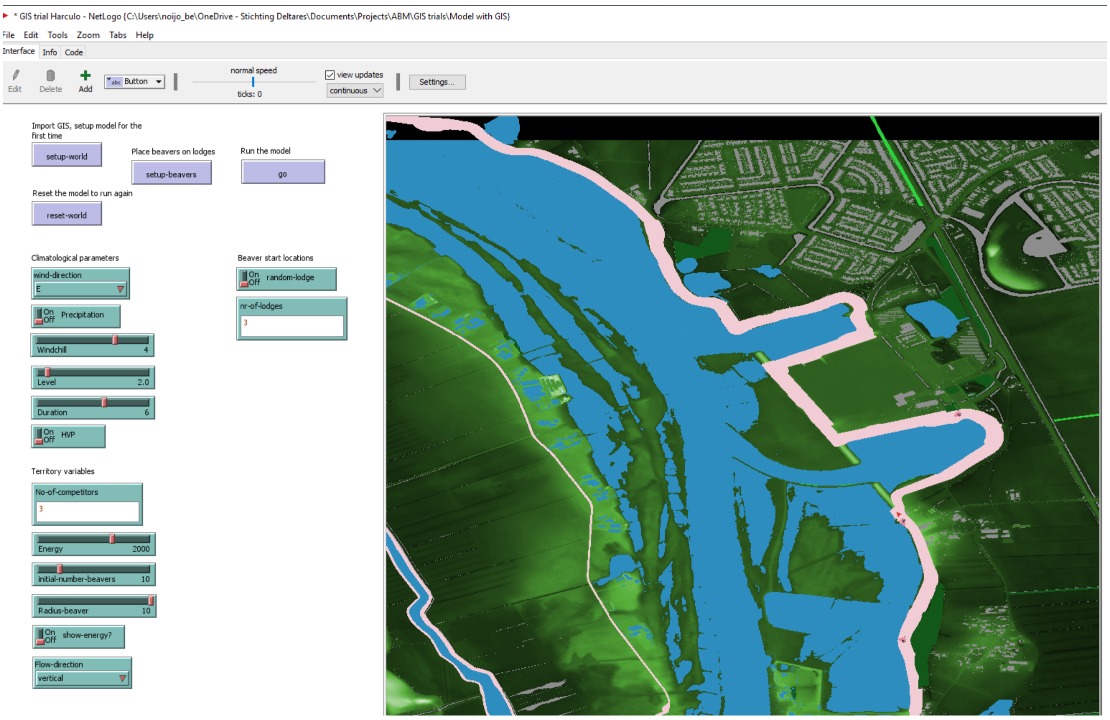

Figure 3.3 Model interface with all inputs shown.

3.3.6 Sub-models

To ensure the model code is easy to read and procedures are executed in the right order, sub-models were created. Compared to the previous version of the model, some sub-models were adjusted and others were added. Table 2.3 shows an overview of the sub-models and whether and how they changed.

Table 3.3 Sub-models and changes compared to previous version as described in (Van den Berg & Natarajan, 2023).

Sub-model	Description	Changed	Changes
Create-flooding	Creates the high-water event that floods the patches within the floodplains and indicates local inundation depth.	Yes	Condition of floodable = true is added to ensure only the area between the river and levees can be flooded.
Decide-to-dig	Weighs the windchill, duration and precipitation parameters against the beaver's sensitivity to those conditions (threshold values) and determines whether the beaver is uncomfortable enough to want to dig.	Yes	It now compares parameters windchill and flood duration with temp-sens and duration-sens per agent to set initial-decision whether or not to dig. In case of precipitation all agents dig.
Find-target-patch	Determines the ideal patch for the beaver to flee to within a search radius that expands continuously by 10% if none is found nearby. The desirability of patches is predominantly determined by wind cover, proximity to woody vegetation and proximity to water, as well as a slope to dig into. The search runs through several loops in order of importance and is based on the assumptions in section 2 of this paper. The maximum search radius is dependent on the initial energy level which is specified by an input parameter.	Yes	Extra conditions were added. The 10% increase loop do it is more likely to find a place nearby. Beaver experts Vilmar Dijkstra and Wesley Overman from the Dutch Mammal Society indicated beavers' preference to river lees (wind cover), proximity to water and proximity to woody vegetation. The order of preference is shown in figure 3-3. Conditions are combinations of those preferences and are different based on the initial-decision.
Calculate-target-patch	Calculates the distance between the beaver's start location and its target patch found in the previous process.	No	
Move	Moves the beaver stepwise towards its target patch and is dependent on the energy level of the beaver and the distance to the target patch.	No	
Avoid others	Diverts the beaver moving direction 180 degrees when it meets a competitor or other beaver within a specified radius.	No	
Energy	Regulates the energy level of the beaver while it is moving towards his target patch. It is dependent on the patch-type since it costs less energy to swim than to walk on land. The initial energy is specified by the user	Yes	Since beavers swim more easily than they move on land, energy was adjusted to decrease 3 per step on flood or water patches and 5 per step on floodplains or levees. This used to be 10 and 3 respectively. This assumption is based on a webinar on beaver burrowing in West-NL by STOWA. An additional condition was added which decreases energy with 10 if the beaver moves outside the levees.
Find-success-failure	Compares the destination of the beaver at the end of the	Yes	If the agent's initial-decision was to dig, and it ended up on a levee, the result is

Sub-model	Description	Changed	Changes
	model run to the initial decision whether to dig and the patch type. This determines whether the beaver dug into a levee or found an alternative safe place like i.e. a treetop. It is also the input of the export function for the burrow coordinates.		'success', the beavers-dug count is increased and the color is set to pink. The coordinates of the patch are exported to a csv file for further analysis. If the initial-decision was to dig and the agent ended up on a floodplain, tree or shrub, the result is 'success' and the color is set to green. If the initial decision was not to dig and the agent ended up on a levee, floodplain, tree or shrub, the result is 'success' and the color is set to green. If the agent did not reach a safe place, the result is set to 'failure'.
Midway-check	Finds a new target patch for the beaver if the first one is already occupied by another beaver or competitor.	No	
Stop-entirely	Stops the beaver moving and then shows statistics of the model run when all beavers in the model either reached their destination or ran out of energy.	No	

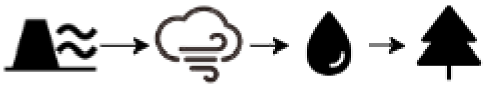

Figure 3.4 Assumed order of preference for safe place selection if the initial decision is to dig. Levees or other hills are preferred. Then, wind cover is important. Beavers like to be near water, and lastly they like to be near woody vegetation. A combination of all of these is preferred but if not available, this is the assumed order of importance on.

3.4 Case study selection

To test the now GIS integrated model, several study areas were selected in which to implement the model and predict holes. With observations made by dike inspectors about burrows in the past, coupled with historical weather data the model could be calibrated. Thus, the selection of appropriate study areas was based on availability of observations, proximity to a weather station (see Figure 3.5), occurrence of beavers and local urgency of animal burrowing resulting in the locations Dodewaard and Harculo. The latter was chosen because the water authority Waterschap Drents Overijsselse Delta (WDOD) shared their recent burrow observations.

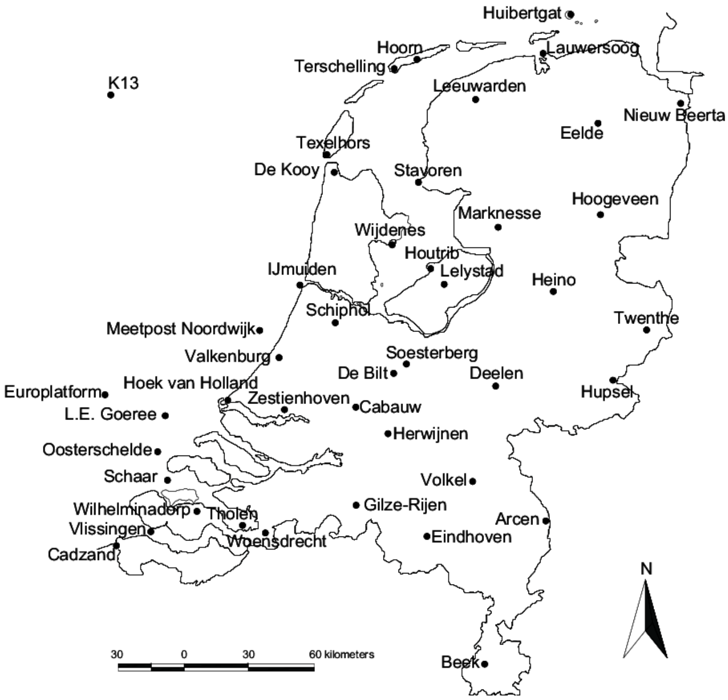

Figure 3.5 Locations of KNMI weather stations.

3.5 Sensitivity analysis and calibration

This research is focused on beaver behavior during high water. Therefore, only those observations of burrows should be selected that are likely to have been dug during high water. This should be done by comparing the expected date of construction with water level records obtained from Rijkswaterstaat[4]. However, due to the lack of observational data on burrows and beaver behaviour and the complexity of the model, calibration of the model is a challenge. For better validation it is necessary to refine the details of the burrow data as collected by levee inspectors.

To validate the model, and to check whether the model results align with the assumed importance of the parameters in Chapter 2, sensitivity analyses were conducted. These analyses were done with different settings of the water level and wind direction parameters, as well as random lodge starting points, as these parameters were expected to have the largest influence on burrow locations. Default settings for model runs for The Netherlands are a south-west wind direction, windchill temperature of 3 degrees Celsius, flood duration of 6 days, initial energy level (so maximum steps) of 1500 moves, 3 beaver families and 3 lodges. The model ran 100 times in case there were 3 beaver families, or 300 times when there was only one beaver family.

In order to run many simulations with different parameters, and prepare for future availability of new data, the model was configured in Python using the library PyNetLogo [9]. This makes it efficient to run a high number of tests, use sampling for multiple parameters, perform statistical tests and create plots. It also improves the user experience if preprocessing the GIS data is done in Python as well.

[4] Historical water level records can be requested through the Waterinfo portal from Rijkswaterstaat. https://waterinfo.rws.nl/

4 Case Dodewaard

4.1 Introduction

The case study area of Dodewaard is located along the Waal River in the Dutch province of Gelderland as shown in Figure 4.2. This location is chosen because it was also part of an earlier research in animal burrowing in levees by van den Berg & Koelewijn (2022), shown in Figure 4.1. The case study area is rich in woody vegetation, such as trees and shrubs and has many ponds and other small water bodies, which are desirable habitat elements for beavers (Graham et al., 2020).

Figure 4.1 Beaver burrow found in earlier research in Dodewaard.

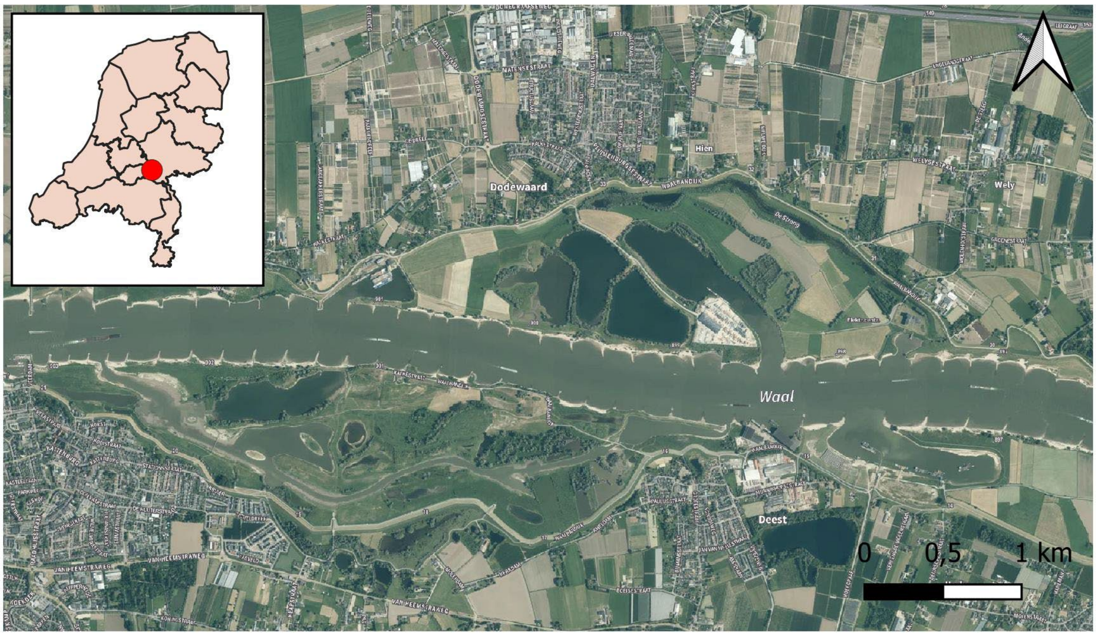

Figure 4.2 Satellite image of the study area near Dodewaard with a reference map of The Netherlands.

4.2 Results

Running the model with default settings and with one beaver family resulted in burrow locations as shown in Figure 4.3. The input settings of one beaver family and constant variables were selected to assess the accuracy of the model. It is not surprising that burrow locations are often near trees along the levees, as well as near small water bodies. Model results were not sensitive to wind direction nor to water level (once the flood plains were flooded), nor to lodge location (see Figure 4.4).

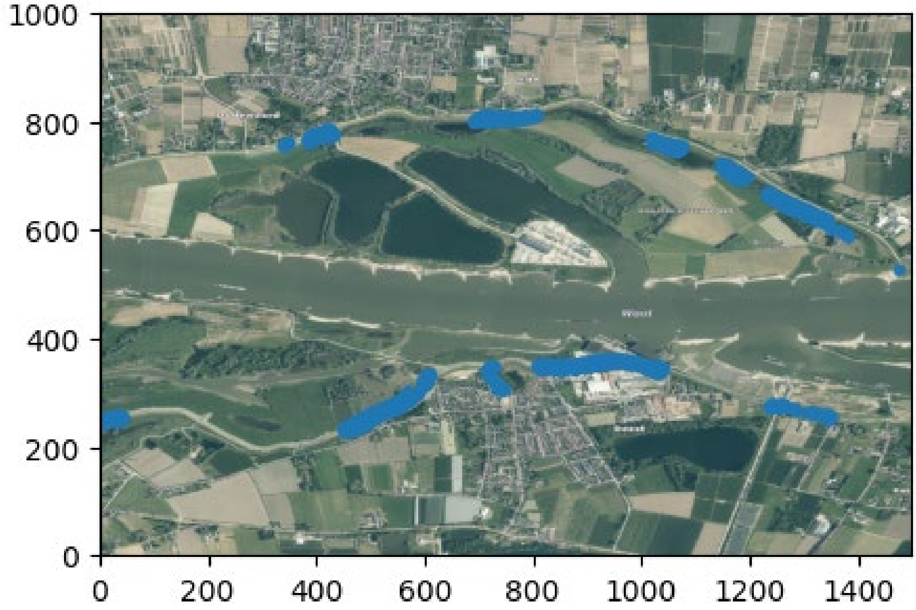

Figure 4.3 Burrow locations resulting from running the model on default settings. The numbers on the axes represent the patches in the model environment.

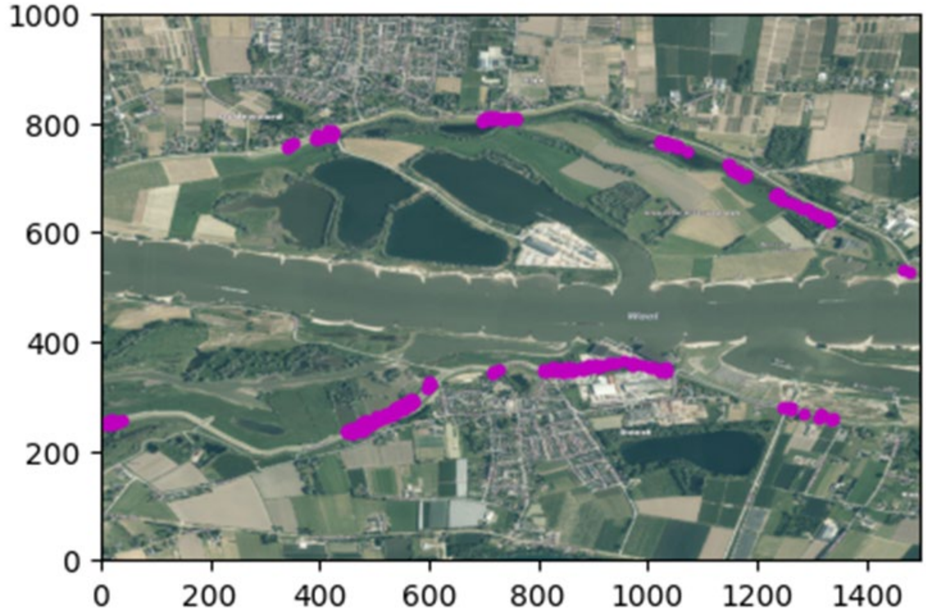

Figure 4.4 Burrow locations resulting from running the model on default settings with random lodge locations. The numbers on the axes represent the patches in the model environment.

5 Case Harculo

5.1 Introduction

Harculo is located along the IJssel river, just south of Zwolle. This case study area was selected because of availability of the burrow data provided by the regional Water Authority WDOD. The landscape elements of the study area are also relevant. The river here has two small harbours around a former power plant, and four ponds. Along the levee on the east side of the IJssel river, some forest patches and other woody vegetation can be found. The burrow observations of recent years are shown in Figure 5.1.

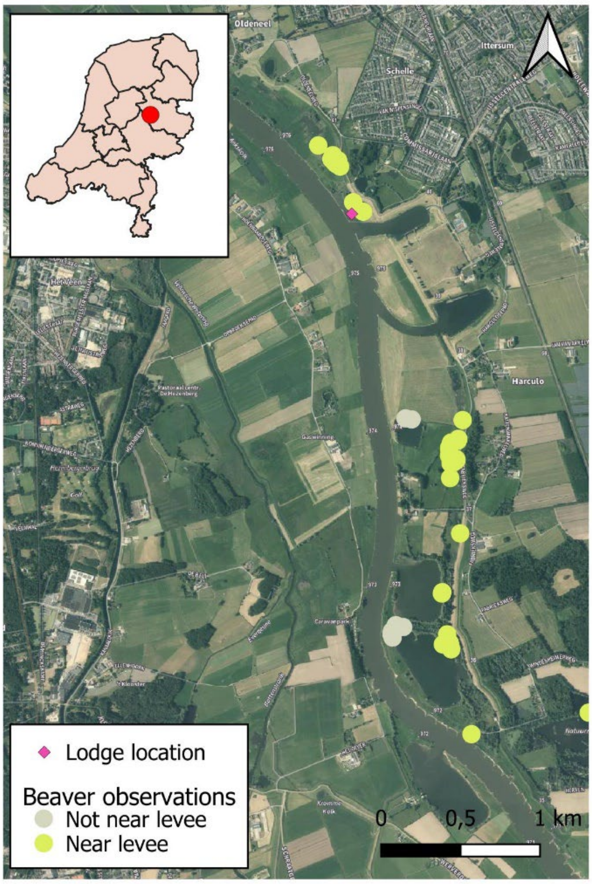

Figure 5.1 Satellite image of the study area near Harculo with a reference map of The Netherlands with beaver burrow observations from WDOD, near and not near levees, and a known lodge location.

5.2 Results

Running the model with one beaver family and default settings resulted in the results in Figure 5.2. The results of this run highlight that randomness in burrow location selection is minimal, as clearly four locations are frequently chosen. As mentioned in section 2 of this paper, wind direction was expected to be a parameter with a large impact on burrow location selection. Therefore, experiments were run with varying wind directions to assess the performance of the model in these different weather situations. However, the results of these runs did not show significant differences, meaning that wind direction does not yet have a high impact on the burrow location selection of the beaver family in this case study.

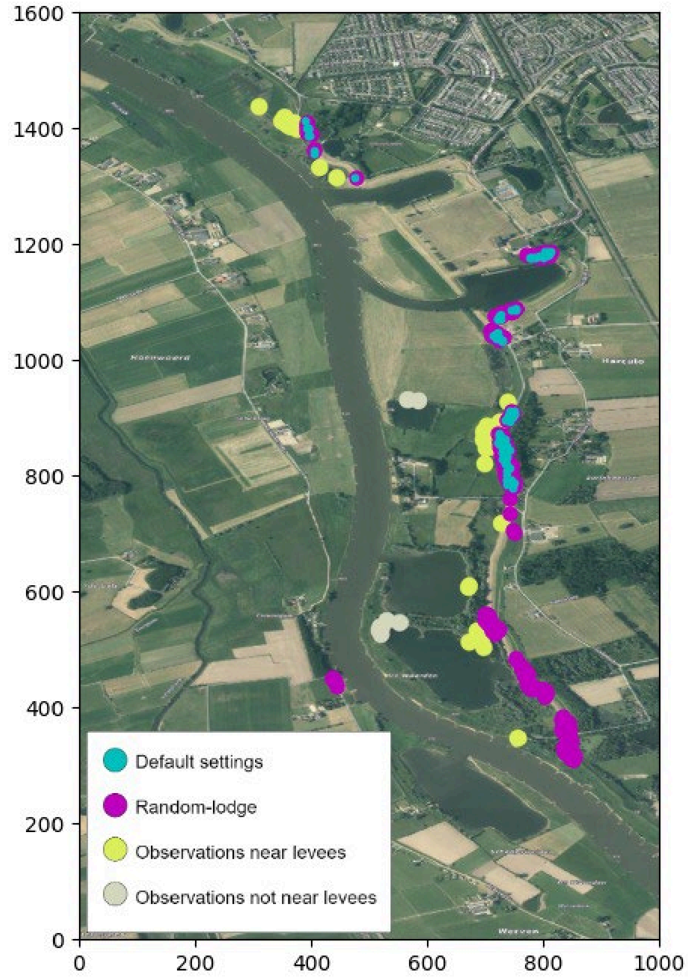

Figure 5.2 Burrow locations resulting from running the model on default settings and with random lodge locations. The numbers on the axes represent the patches in the model environment.

A variable with a large impact in the model is the lodge location, which is the starting point of the beavers in the model. Default settings only included the single known lodge (see in Figure 5.1). Running the model with the random lodge function resulted in burrows extending to the southern part of the study area as well, since in this case lodges will be placed randomly across the floodplains, preferably close to woody vegetation and water bodies. This includes the southern part of the study area even though there is no currently known lodge at that location. Thus, when no lodge locations are known in a study area (which is often the case), the random-lodge function can be used, as it does not seem to decrease accuracy as long as the number of model runs is large enough.

6 Discussion

Based on observational data from the WDOD Water Authority for the Harculo case study, a comparison between the model output and observed burrow locations could be made (Figure 5.1). Graphically, two out of the four burrowing areas resulting from the model with default settings seem to be in accordance with the observations in the field. Additionally, in the random-lodge model run, the burrows found in the southern part of the area are also in line with the observed burrow locations.
The data from WDOD do not differentiate between normal and high-water situations, which means that the assumption could be made that the burrows close to the normal water level (in the floodplain) can be excluded from the comparison as those would be flooded in high-water situations.

Draft conclusions can be drawn, but it is evident that more and more detailed observational data is needed to perform the calibration of the model. The need for more calibration is illustrated by the lack of differences in model results under different parameter settings, which is not in line with expected results based on expert knowledge. More data, and specifically, more detailed data of the beaver behaviour is needed to improve the model. At this stage, the model does not indicate a major role of the wind direction in the burrow location selection of beavers during a high-water situation. However, from consultation with beaver experts, we know that it should play a big role. As calibration with climatological data and burrow observations was not yet possible, the model could not yet be made more accurate in this regard, but this is highly recommended in an update of the model once data becomes available. When this happens, it is also advisable to include or adjust for wind speed in the updated model, since it is not likely that wind direction has a big role if the wind speed is very low.

Beaver behaviour is still largely unknown, and further research is constantly being carried out. Following the development in this area, the model can be adjusted to new knowledge and further sub-models could be added. It is expected that especially the Energy and Decide-to-Dig sub-models can be improved with further understanding of beaver behaviour. The Dutch Mammal Society has announced their intention to implement tracking devices meant to follow beaver movement. With this data, the model could be improved tremendously, for example by incorporating territories.

The random-lodge function seems to give realistic results, which can be used when a field area is not widely researched yet and not a lot is known about the different beaver territories in that area.

Various organisations are working on the development of high-water refuge spots (HVPs), which serve as alternative safe places for beavers, discouraging them from digging into the levees. The model could be used to predict where these HVPs would be most effective.

Coupling the Agent Based Model with a flow velocity model or a flood model could be interesting, since experts from the Dutch Mammal Society have indicated that lees, or spots in the river with limited flow velocity, seem to be preferred spots for beavers. Additionally, incorporating flow velocities would discourage the beavers in the model to cross the river, which is closer to their natural behaviour.

7 Conclusions and recommendations

7.1 Conclusions

An Agent-Based Model of the behaviour of beavers during high-water has been built. This model predicts patterns of locations including probabilities where beavers may burrow during high-water. The method can also be used to derive probabilities of burrows that are input for a safety assessment of a levee. In subsequent steps from beaver observations until its behaviour under high-water conditions, the failure probability of a levee in these situations where burrowing may occur may be assessed.

7.2 Recommendations

The agent-based model is running and will give insight into the effect of the behaviour of beavers during high-water on the levees.
For further development of the model the following recommendations and proposed extensions are important:

For further development of the model the following recommendations and proposed extensions are important:

- Including river flow velocity in the model.
- To obtain a better calibration of the model by, it is necessary to obtain more and more detailed data and have more insight in beaver behaviour. To facilitate the process of obtaining accurate data for calibration, a detailed questionnaire has to be prepared, and dike inspectors or other observers should be trained for using these questionnaires correctly. During high water situations there is not always time for this, but in that case an estimate afterwards is better than no information.
- Comparing observations with model results will further validate the model and help to find the key aspects and parameters that result in sound predictions [12].
- - Using an updated version of the model to assess HVP placements.
- Publishing the model on Netlogo Modelling Commons, an online platform for open-source ABM. In a later stage, after calibration is finished, the model could be integrated into a dashboard, for an easy user experience, since the model was created with the intention to be shared with professionals in the field such as dike inspectors of water authorities.

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