# Floating High-water Beaver Refuges

THESIS INTERNSHIP: RESEARCH REPORT


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# Summary

From the very beginnings of the Kingdom of the Netherlands, water management has been a topic of prime importance. This subject has taken even greater priority in recent times due to climate change and the consequent erratic weather and sea-level rise. The measures taken to ensure water safety have been allocated ever-greater budgets to handle the diverse issues.

One of these emerging issues is the rise in Eurasian beaver (*Castor fiber*) populations in the Netherlands. They are an indigenous species that faced a local extinction two hundred years ago but who have since been reintroduced and have re-established themselves across their former range.

The conflict arises whereby their habitat and living requirements clash with our (human) water management principles. This takes the form of burrowing in dykes, which greatly weakens the integrity of the structures and increases the risk of failure, the result of which could lead to massive losses in terms of life as well as property.

This research paper intends to guide the reader through an exploration of the development of floating high-water refuges, which seek to be a compromise between the beaver’s need for shelter during flooded periods and human society’s need for increased water safety in the years to come.

The methods used to collect data are primarily literature reviews, meetings and interviews with involved professionals and map analyses. Provided this data, technical and functional requirements for the structures were proposed, from which preliminary design concepts were made. These were then subjected to iterative hand and software calculations to determine the static stability of the structures during extreme river discharges.

The result of this was that the final structure met the technical and functional requirements. The caveat on predicted success is the limited information available on the use of such structures by wildlife. Hence, real-world tests are required to conclusively determine their adoption.

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# 1. Introduction

This report means to outline a possible strategy to solve the safety hazards caused by beavers to dykes and general water safety.

Beavers were driven to extinction in the Netherlands in the early 19th century. The primary driver for this was overhunting. As per Nolet and Rosell (1988), the last beaver was shot at Zalk aan de IJssel near Zwolle in 1826.

They are relatively easy to locate and therefore hunt or cull, especially in autumn when they fell trees and build or repair their lodges, dams, and food caches, or during ice cover in winter. The beaver was mainly hunted for its pelts, the chemical substances from its castor sacs (castoreum, used as a medicine and a base aroma in perfume), and its meat (Djoshkin & Safonov, 1972). Being an aquatic animal, in the Middle Ages, it was classified as a fish and was therefore allowed to be eaten on Friday. Hence, they were driven to near extinction across much of Eurasia, with only a few remnant populations left surviving.

A series of conservation measures were then enacted, beginning with hunting prohibitions across every country where beavers still survived (Nolet & Rosell, 1998). This measure was slightly too late for most countries, and so repopulation projects were begun (Figure 1). The early reintroductions were aimed at the re-establishment of a game species to be harvested for its fur; however, from the 1970s onwards, the animals were reintroduced more and more for ecological reasons, i.e., because of the significant impact beavers can have on their surroundings in being able to fell mature trees and modify water levels (Kollar & Seiter, 1990).

| Country | Extirpation | Protection | Reintroduction |
|---|---|---|---|
| Austria | 1869 | — | 1970–90 |
| Belarus | Remnant | 1922 | — |
| Belgium | 1848 | — | — |
| Britain | 16th century | — | Proposed |
| Croatia | ? | — | Under investigation |
| Czech Republic | ? | ? | 1991 |
| Denmark | ? | — | Under investigation |
| Estonia | 1841 | — | 1957 |
| Finland | 1868 | 1868 | 1935–37 |
| France | Remnant | 1909 | 1959–95 |
| Germany | Remnant | 1910 | 1936–40, 1966–89 |
| Hungary | 1865 | — | — |
| Italy | 1541 | — | — |
| Latvia | 1871 | — | 1927–52 |
| Lithuania | 1938 | — | 1947–59 |
| Mongolia and China | Remnant | ? | 1959–85 |
| Netherlands | 1826 | — | 1988–95 |
| Norway | Remnant | 1845 | 1925–32, 1952–65 |
| Poland | 1844 | 1923 | 1943–49, 1975–86 |
| Russia | Remnant | 1922 | 1927–33, 1934–41, 1946–64 |
| Slovakia | ? | ? | — |
| Sweden | 1871 | 1873 | 1922–39 |
| Switzerland | 1820 | ? | 1956–77 |
| Ukraine | Remnant | 1922 | — |

*Figure 1: extirpation, protection, and reintroduction dates across Europe (Source: Nolet & Rosell, 1988)*

The reintroduced beavers spread quickly over their former range owing to the fact that their habitats were still largely present, and moreover due to their ability to survive and reproduce even in cultivated and other human-controlled areas (after the initial build-up phase).

The latter point is the focus of this research. The beaver populations introduced in the Netherlands between 1988-1995 have been steadily growing, ultimately leading to more human-beaver conflicts, particularly concerning the domain of water safety. In light of the safety risks they pose, measures are to be taken to minimise the conflict between their activities and the responsibilities of water management bodies. However, because of the beaver's status as a protected animal in the Netherlands, control measures are problematic, and must be deemed absolutely necessary for an exemption to be permitted.

The control measure that makes for the focus of this research is the installation of high-water refuges (Figure 2).

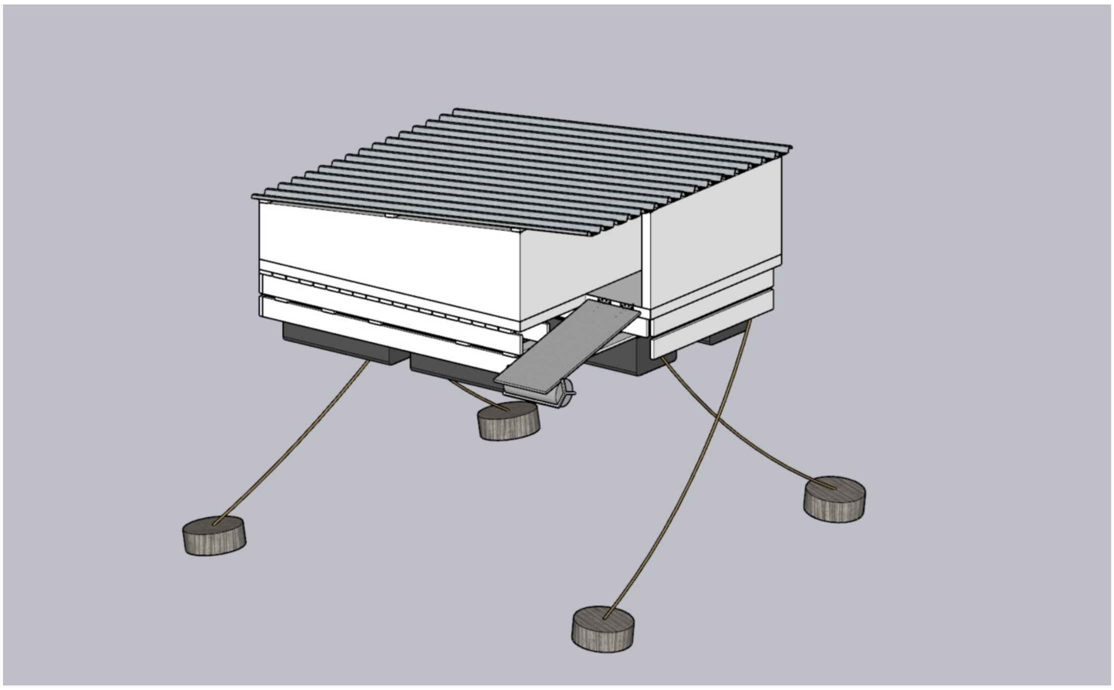


*Figure 2: conceptual impression of a high-water refuge*

High-water refuges (hoogwatervluchtplaatsen/HVPs) are structures built to shelter beavers as an alternative to burrowing in dykes during periods of extreme river discharge, such as the conditions experienced in the Meuse (Dutch: Maas) in July 2021. During such an event, the beavers' burrows and dens in the lower floodplains will become inundated, forcing the beavers to flee and move to higher locations where they can "sit out" the high water. Generally, they first move to the top of their den. Should this be fully submerged, they move to higher ground bodies in the area or even trees in very rare cases, where they build a nest in the lower limbs out of twigs and branches.

Nevertheless, dykes are often the victim of burrowing during high water periods as they lie higher than the floodplains. The probability of their being burrowed in is greatest when all other parts of the floodplain have been submerged (Dijkstra V. , 2017). Naturally, this causes problems for water managers as the beavers dig into the dykes, making them susceptible to failure.

As such, the primary objective of the high-water refuge is to protect the dyke, not the beaver.

Although uncommon, the beavers may also burrow in dykes during regular water levels (where the foreland of a dyke is short). This is more acceptable than the former case as there is sufficient time to intervene before the high-water season.

Over the years, the damage caused to flood defences has become a growing issue as viable locations for the beavers to escape the rising water levels have reduced, coupled with a rise in beaver distribution and populations across the country (Figure 3). Because of this, there is an ever-increasing risk of damage to the flood defences.

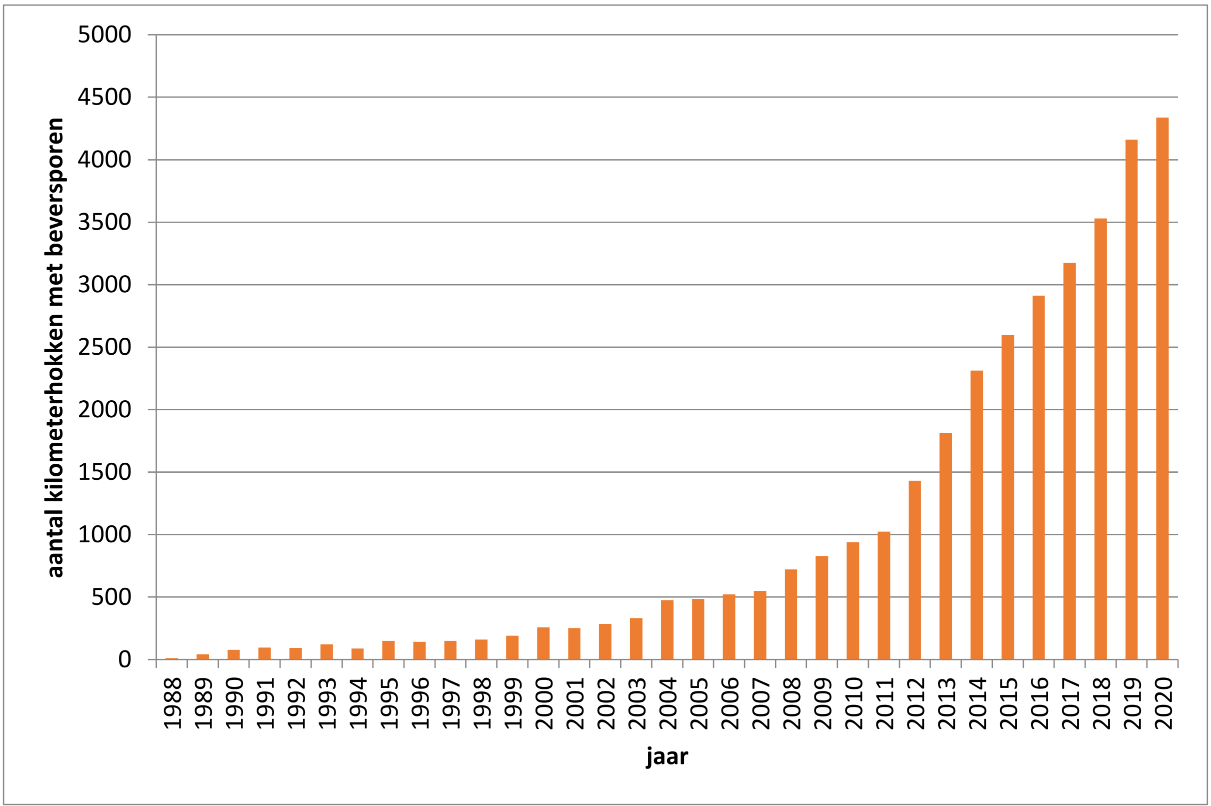



*Figure 3: number of 1 km2 survey squares with beaver spoors between 1988-2020 (Source: Dijkstra V. , Polman, van der Jagt, van Oene, & van der Meij, 2021)*

## 1.1.Goal

The goal of this research is to explore different variants for floating high-water refuges. So far, beaver refuge concepts have been aground structures that allow the beavers to burrow above water level. However, the subject of (stationary) floating shelters shall now also be explored. Optimally, these will detract beavers from burrowing in dykes by providing a suitable alternative.


*Figure 4: overview of areas managed by the Waterschap Aa en Maas*

The graduation internship was conducted through the Water Safety Department of the Waterschap Aa en Maas. This water authority is charged with the management of water in the eastern part of North Brabant (an area covering more than 160,000 Ha). It is responsible for the safety of 744,000 citizens across 22 municipalities, ensuring water quantity and quality, as well as safety from flooding through the management of more than 300 km of flood defences (Aa en Maas in cijfers, 2022).

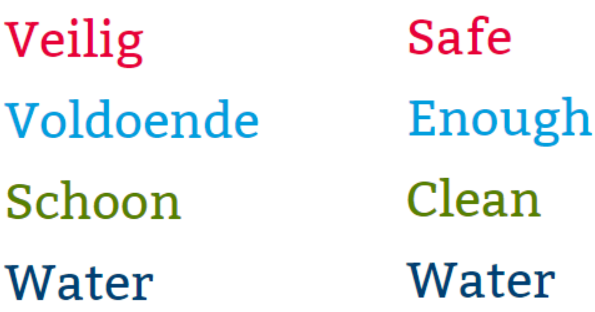



*Figure 5: summary of the tasks of the Waterschap Aa en Maas*

The knowledge and experience built up from this project shall be shared with other flood defence managers (water boards and Rijkswaterstaat).

Looking at the broader picture however, the research pilot was taken up by representatives of the waterboards Rivierenland, Drents Overijsselse Delta, Vallei en Veluwe, Aa en Maas and the Zoogdiervereniging (Mammal Society).

In addition, contacts have been made with representatives of other water boards and Rijkswaterstaat has also expressed an interest in the pilot. There is also a connection to the Kenniscentrum Bever (Beaver Knowledge Centre) and communication can also partly take place via the STOWA (who are also participating in the Bever Kenniscentrum).

## 1.2. Research questions

The primary research question is:

*What refuge design is the most viable?*

This is further broken down into specific sub-questions:

1. **What is the most optimal choice of materials and components?**
   An MCA shall be used to assess the materials' behaviour in relation to desired properties.
2. **Where should the structure be built?**
   The influence of stakeholders, locations of active beaver sites and the topography of the chosen area shall be evaluated to determine this.
3. **Will the structure withstand the expected loads?**
   Appropriate deck loads (beavers) and their distributions will be accounted for to determine sufficient buoyancy and stability in zero flow conditions (hydrostatic stability). Moreover, the conditions at the chosen installation location(s) shall be analysed and translated into forces applied to the structure to ensure stability when subjected to waves.

# 2. Theoretical framework

Key concepts from the research question and the secondary question shall be addressed here using a literature review of select articles, journals, reviews, reports, and legislature. The relevant theories are evaluated and explained in so far as they are represented in the research.

## 2.1. Beaver ethology

Eurasian beavers (*Castor fiber*) are large rodents known for their industrious behaviour, primarily in the domain of dam-building. These primarily crepuscular creatures are herbivorous foragers, whose diet is composed of herbaceous plants, tree bark and sedges. They forage on land for food and building materials but are most active in water. Factors that favour beaver presence in an area are woody riparian vegetation, relatively flat channel gradient, small maximum bed-material grain size, and high channel sinuosity (Gorczyca, Krzemień, Sobucki, & Jarzyna, 2018).

Building their dams across freshwater streams, rivers and channels, their aim is to impound the water and create a suitable water level for them to build their den or lodge, whose entrance they build underwater. The flooded wetland also has the added benefit of creating a suitable foraging area, as they dig up channels through their territory to increase their mobility through the range. Because of the effect they have on other organisms in the ecosystem, they are considered keystone species.

Adult beavers live in monogamous pairs and will reproduce once per year from the age of three years, resulting in litter sizes of one to four kits (Campbell-Palmer, et al., 2016). When older, the young animals help their parents build and repair dams, as well as to raise newly-born kits. They leave their parents' territory at the age of two years to establish their own family. Beavers distinguish between territories by use of scent mounds, little piles of mud, debris and castoreum, an exudate used as a tincture in some perfumes.

## 2.2. Ecological importance

The positive effects of reintroducing "extinct" species are increasingly recognized. This concerns in particular the effects that such species have on the development and maintenance of other communities through the role they play in the ecosystem. It turns out that many natural areas are in fact incomplete ecosystems which miss important functional elements. Certain animals play an important role in these ecosystems because they have a strong influence on the structure and composition of vegetation or because they influence the population development of other species. Beavers are such an animal.

As stated previously, they act as keystone species in their habitats due to the significant influence they have over their environment. Referred to as ecosystem engineers (Wright, Jones, & Flecker, 2002), beavers maintain high species richness in the landscape scale by increasing habitat heterogeneity. Their dams dramatically alter riparian landscapes, allowing the survival of other species. Their dam-building behaviour, their coppicing of trees as well as their burrowing activities all serve to create a more dynamic and complex ecosystem in their habitats.

Although beavers are highly adaptable and can modify many types of landscapes, they prefer slow-moving water with stable depths of around 60cm. Where these habitats are unavailable or are already colonised by other beavers, they will colonise narrower watercourses and construct dams to create suitable habitats (Campbell-Palmer, et al., 2016). Most watercourses in the Netherlands are relatively slow-moving, and so beaver dams are not as rife as in other Eurasian waterways.

Nevertheless, the positive habitat creation and biodiversity benefits created by beavers can be exemplified by key activities such as tree felling, with the associated opening in the tree canopy which spurs vegetation growth and plant biodiversity. Where gnawed stumps sprout again, there is a cyclical forest rejuvenation. Herbivores such as roe deer forage on the young foliage of sprouting stumps, which also become overgrown with different species of fern and lichen. Moreover, the creation of dead wood provides breeding and feeding sites for a host of invertebrates and their predators. The nutrient cycle in these ecosystems is increased by the accelerated decomposition of herbs and woody plant parts which enriches the soil structure.

Dam building, on the other hand, creates new wetlands, slows water to encourage invertebrates, and provides spawning ponds for fish and amphibians (Campbell-Palmer & Jones, Bringing beavers back, 2014). In addition, insects such as dragonflies are attracted by the slow-moving water, and so are various amphibian species and birds such as black tern, kingfisher, and yellow wagtails.

Lastly, their (abandoned) burrows and lodges can be inhabited by small predators such as polecat, weasel, and ermine, possibly also otters. Muskrats too have been known to coexist with beavers in the same den.

To summarise, beavers offer ecological value to their habitat and promote greater biodiversity, but at the expense of water safety.

## 2.3. Animal conservation (status)

Eurasian beavers (*Castor fiber ssp. albicus*) are a protected species in the Netherlands, as outlined by the Nature Conservation Act: Species Protection Regime of the Habitats Directive (Beschermingsregime soorten van de Habitatrichtlijn, 2015). The applicable prohibitions are set out in Articles 3.5 and 3.6, which forbid to:

1. Intentionally kill, capture, or intentionally disturb the referred animals in their natural range
2. Deliberately destroying or collecting eggs of the referred animals in nature
3. Damage or destroy breeding grounds or resting places of such animals
4. Intentionally plucking and collecting, cutting, uprooting or destroying plants of such species in their natural range
5. To possess for sale, transport for sale, trade, barter, or offer for sale or barter animals or plants of the said species (not applicable with species that are demonstrably bred or cultivated)
6. To possess or transport animals or plants other than for sale (not applicable with species that are demonstrably bred or cultivated)

The beaver is also protected by several other legislations, such as the EU Habitats Directive annexes II and IV, the international Bern Convention on the Conservation of European Wildlife and Natural Habitats, the 2004 IUCN Red List of Threatened Species (categorised as near threatened), by the Target Species List of the Netherlands (selected based on international significance in the Netherlands and overall rarity) and finally by the Government Gazette of 2009 where it is included in the Red List of Mammals as a sensitive species. Therefore, for action to be taken against beavers in the interest of water safety, applications must be made for exemptions in the case of absolute necessity.

The fifth line of article 3.8 of the Wet Natuurbescherming (2021) provides that for Habitats Directive species (Habitatrichtlijn Bijlage IV, 2015), including the beaver, an exemption can only be permitted in certain conditions.

A waiver or an exemption will only be granted if all the following conditions are met:

a. There is no other satisfactory solution.
b. It is needed:
    i. in the interest of protecting wild flora or fauna, or in the interest of preserving natural habitats.
    ii. to prevent serious damage in particular to crops, livestock farms, forests, fishing grounds, waters, or other forms of property.
    iii. in the interests of public health, public security, or other imperative reasons of overriding public interest, including those of a social or economic nature and including significant beneficial effects for the environment.
    iv. for research and education, repopulation, or reintroduction of these species, or for the breeding necessary for that purpose, including artificial propagation of plants.
    v. to enable, under strictly controlled conditions, the capture or retention, selectively and within certain limits, of a limited number of certain animals of the designated species determined by the exemption or exemption, or a limited number determined by the exemption or exemption to pluck or have in possession of certain plants of the designated species.
c. The aim is to maintain the populations of the species concerned in their natural range at a favourable conservation status.

Although beavers are no longer as extensively hunted in Europe as they were prior to the early 19$^{th}$ century, they still face several pressures that the above legislature aims to curb.

For example, due to their low distribution, a disaster in one of the areas they inhabit (chemical pollution, disease) will have a major negative impact on the entire population (Bever - Castor fiber ssp. albicus, 2015). Another point of sensitivity is the disturbance of their land habitats. In practice, it has already become clear that heedless or less-thorough dyke and foreland management has cost beavers their habitats. Furthermore, beavers are territorial and therefore must travel relatively large distances after leaving their parents' dens to establish their own families. Physical barriers to the ecological connections pose a potential threat, for example, a blocked culvert forces the beaver to move over land, with all the associated risks (traffic). Moreover, dusk and night riverine recreation may disturb beaver families. They can be hit by a ship's propellers. Also, the presence of dogs may hinder settlement through fear of predation.

Nevertheless, as per the Kader Zorgplicht Primaire Waterkeringen (2015), the duty of care for primary flood defence systems means that the water manager has the statutory duty to ensure that the primary flood defence system meets the safety requirements and to ensure the necessary preventive management and maintenance. The flood defence system is thus regularly inspected by the manager to assess whether the condition of the defence still complies with the (design) requirements. If the physical condition of the barrier no longer meets the (design) requirements due to, for example, technical obsolescence or (storm) damage, the manager must take the necessary measures. In this case, that refers to the minimisation of beaver-caused damage.

In summary, the control of beavers is a sensitive topic with much legislation to address if the dyke and beaver are both to be protected successfully.

## 2.4. Human-animal conflicts

The vast majority of these conflicts tend to occur with farmers and foresters (farming conflicts are more applicable in the Netherlands), within 20 metres of the water's edge. The creation of 20m buffer zones around water courses and bodies can serve to greatly ease such impacts. Long-term changes in land practices such as not farming to river edges or canalising waterways would also greatly benefit many other species (Campbell-Palmer & Jones, Bringing beavers back, 2014).

Since the Netherlands is rich in water and woody vegetation is present along many waterways, a large part of the Netherlands can be regarded as potential habitat. This comes hand in hand with excavation damage to banks (subsidence of machines), hydrological damage due to dam construction (damage to agriculture), and feeding and gnawing damage (damage to horticulture/forestry).

Killing or removing the beavers from the locations where they cause damage is not a lasting solution as other families will simply replace them (Nolet & Rosell, 1998). A more sophisticated way to reduce damage is fertility control. This works well with beavers as breeding pairs generally mate for life (10+ years), only replacing a partner when they die or are displaced after territorial disputes (Campbell-Palmer, et al., 2016). Tests performed on North American beavers (*Castor canadensis*) proved successful provided that the animals were only sterilised and not castrated, i.e., their hormone system was kept intact (Campbell-Palmer & Jones, Bringing beavers back, 2014).

## 2.5. Water safety

The areas currently experiencing the brunt of beaver-induced risks lie mostly in the southeast of the Netherlands, where beavers are most densely populated (Figure 6). Since their reintroduction, beavers have established themselves in every province in the Netherlands.

The potential consequences of their spread are herein established.

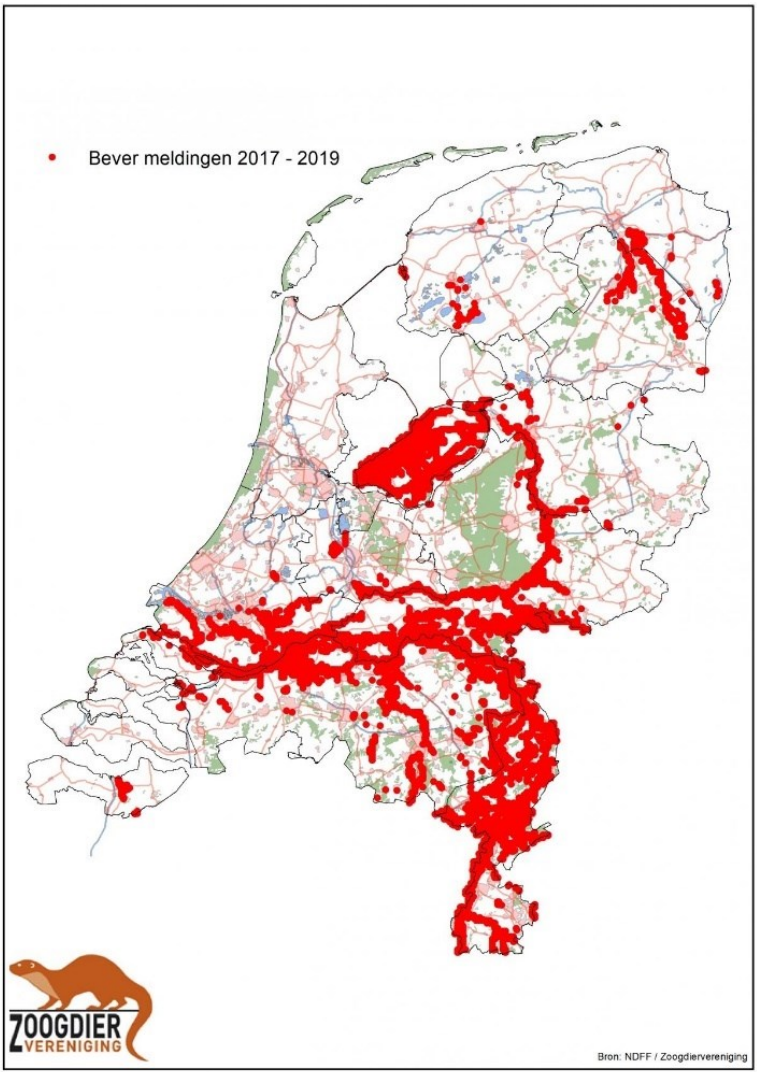



*Figure 6: beaver reports between 2017-2019*
*(Source: Zoogdiervereniging/Nationale Databank Flora en Fauna)*

Among the risks posed by beavers are:

i. Damage to the outer slope and the (hard) revetment, causing erosion of the outer slope and eventual erosion of the dyke body
ii. Undermining of the outer slope, resulting in shear failure of the slope
iii. Damage to and undermining of the inner slope, causing shear collapse of the slope
iv. Excavation of berms, causing subsidence
v. Sagging of the crown due to excavation, causing overflow during high water situations
vi. Digging through the dyke body, causing seepage
vii. Breakthrough of small quays (particularly along fishponds and flood plains)
viii. Tree felling

ix. The dams they build can lead to impoundment, reduced water supply and discharge, reduced water storage capacity, and damage to crops on adjacent plots (Beverprotocol, 2020).

Furthermore, damage to the dykes is typically not visible during high water periods as the entrances are dug under the surface of the water. This increases the danger posed as the risks are not immediately apparent.

Therefore, due to the beaver-caused damages and risks mentioned, it is of great import that measures be taken in the name of water safety, water quality and biodiversity. The actions taken to minimise these risks include:

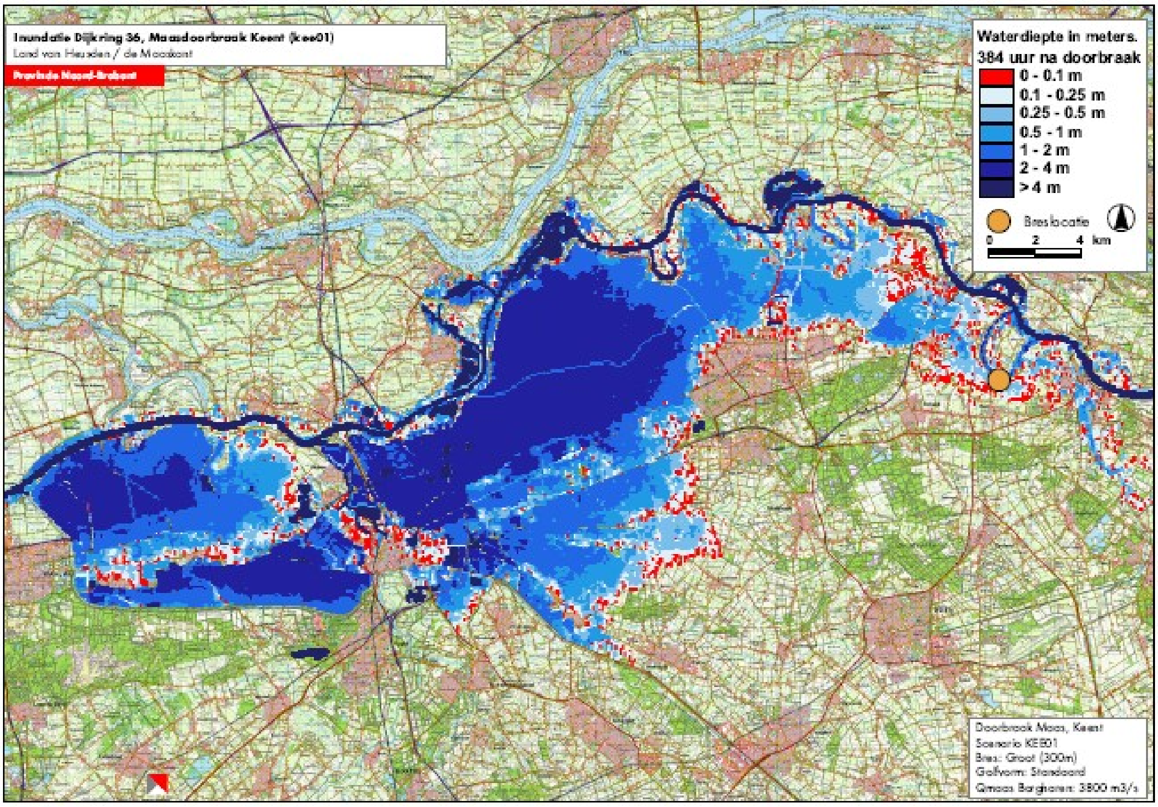
- Development of high-water refuges (Dijkstra & Polman, Oplossen en preventie van beverschade, 2018)
- Installation of sheet piles and wire mesh in the ground to limit burrow length
- Excavation of dens and filling in
- Covering the slope in large stones or some other hard revetment
- Redirecting the waterway away from dykes and roads to minimize damage (beavers do not build dens far from water)
- Lowering or levelling out steep banks to make burrowing less attractive
- Removal and relocation of beavers. This is generally not preferred as another beaver family will simply replace the relocated family.

The following methods are also used to limit other types of beaver damage, namely to trees and small waterways:

- Fencing off culverts to prevent plugging by beavers
- Lowering dams by hand, rake, or crane (primarily in winter when dams are higher due to irregular water regime)
- Complete removal of dam (the removed material should not be left close by, lest it be used to rebuild the structure)
- Deepening of waterway to allow den entrance to remain submerged
- Use of “beaver deceiver” pipes to drain water from beaver dams
- Application of deterrent paste on tree trunks
- Installation of wire mesh around trees (flexible to allow growth of tree)
- Increase distance between vegetation and roadways
- Discouraging settlement by planting tree and shrub species that beavers are less able to digest
- Installation of L-shaped fences around plots of vulnerable trees and shrubs

Simulations for primary flood defences in the province of North Brabant were drawn up by HKV and later published in 2016 by the (then) Ministry of Infrastructure and the Environment (Dutch: *Ministerie van Infrastructuur en Milieu*). They were prepared in the context of updating flood risk management standards of the primary defences, following calculations of standard heights based on a Local Individual Risk on flood fatalities of $10^{-5}$.

The image on the following page (Figure 7) shows the situation after a normative dyke breach of the Oude Maasdijk at Keent (irrespective of the cause of breach).




**Gevolgen van overstromingen**

| | | |
|---|---|---|
| Evacuatiefractie (onderkant bandbreedte) | [-] | 0.59 |
| Mortaliteit bij overstroming vanuit dit traject | [%] | 1.3 |
| Mortaliteit bij overstroming vanuit andere trajecten (overlap) | [%] | 4.3 |
| | | |
| Getroffenen (jaar 2011) | [aantal] | 250 000 |
| Slachtoffers (jaar 2011) | [aantal] | 420 |
| Economische schade (jaar 2011) | [mln euro] | 21 000 |
| | | |
| Getroffenen gemonitariseerd (jaar 2050) | [mln euro] | 6 000 |
| Slachtoffers gemonitariseerd (jaar 2050) | [mln euro] | 6 000 |
| Economische schade (jaar 2050) | [mln euro] | 43 000 |
| Totale schade (jaar 2050) | [mln euro] | 55 000 |

*Figure 7: simulation of consequences of Oude Maasdijk breach at Keent (Source: Ministerie van Infrastructuur en Milieu, 2016)*

Of course, the damages suffered differ greatly between agricultural/natural hinterlands or urban ones, but as seen above, the damages suffered by a primary defence breach can run into tens of billions of euros. Regional defence breaches will cause only a fraction of this damage, but that can still have a setback in the order of millions of euros (Beverprotocol, 2020).

In addition to the costs of consequential damage, there are also costs involved in damage repair when closing up burrows and dens in a situation where the damage has not yet resulted in a dyke breach. These costs are highly dependent on location and vary between €2,000 and €7,500 (Beverprotocol, 2020).

## 2.6. High water refuges (hoogwatervluchtplaatsen/HVP)

Artificial refuges are human-made structures that aim to create safe places for animals to breed, hibernate, or take shelter in lieu of natural refuges. These structures are purposefully designed and meant as human-made substitutes for (or supplements to) natural habitat structures, and are usually deployed in degraded, disturbed, or modified environments. They are designed to replace or supplement those naturally occurring that are used for a specific function, rather than create an "enclosure" or radically different habitat.

Examples of such structures are artificial nests, hollows, reefs, dens, and other refuges where animals can bask, rear offspring, hibernate or shelter from predators and other environmental stressors.

As explained by Watchorn et al. (2022), the design of these shelters proves complex, as many factors have to be considered, such as:

i. Position of the structure within the landscape
ii. Orientation to wind/currents/waves
iii. Physical dimensions
iv. Colour
v. Microclimate dynamics
vi. Structural complexity
vii. Hardness
viii. Porosity

Additionally, in-situ real-world experiments are required beyond designing and building the structures. In the case of this research, where the ability to shelter beavers under high-water conditions is sought, the design is further complicated by the fact that it is difficult to predict when the next high-water period will be. These conditions are required to satisfactorily analyse whether the beavers will take to the shelters provided.

High water refuges (hoogwatervluchtplaatsen/HVP) are a measure used in low-lying areas that become submerged during flooded or high tide periods. Typically, they are used as resting and feeding zones for birds in coastal areas, but here the idea is explored to protect dykes against beaver burrowing during periods of high river discharge.

At high tide, beavers seek high sheltered and undisturbed places. The presence of vegetated elevations in the floodplains can prevent them from digging in the dike. These areas which do not flood are suitable as they present an alternative to digging in the dykes. A point of interest is that beavers are highly territorial and will not tolerate other unrelated beavers within their territory. This means that there must be a suitable high-water refuge for each territory, otherwise, there is a chance that beavers will dig a burrow in a dike (Dijkstra V. , Hoogwatervluchtplaatsen belangrijk voor duurzaam samenleven met bevers, 2017).

As for attracting the beavers to the high-water refuges, scent marks from related animals could be used. This substance, called castoreum, can be expressed from the beavers' castor sacs and deposited in or around the high-water refuge. Enticing foods such as apples or Eurasian aspen branches could be used in tandem (V. Dijkstra, 2022).

### *2.6.1. Soil body HVP*

To date, designs have been made for soil bodies that serve as beaver refuges. The structures are small hills covered in various shrubs and small tree species, devised in such a way as to mimic the beaver's natural den or lodge.

*Figure 8: soil body high-water refuge*
*(Source: Willy de Koning)*

The considerations taken for their design are (Dijkstra 2021, Dijkstra & Polman 2018, Dijkstra & Popelier 2021, www.kenniscentrumbever.nl):

i. **Height of the high-water refuge**
In order to be effective, even if there is a build-up of waves due to strong winds, a high-tide refuge must remain at least a metre above the water (Dijkstra V. , 2017). This allows sufficient dry ground for the animals to burrow above water level. How high the HVP must rise above ground level then depends on the flooding frequency considered.

ii. **Shape of the surface**
The shape of the structure should be designed such that it does not create much turbulence relative to the water currents. A tear-drop shape would be optimal to reduce backwaters while still retaining a large surface area.

iii. **Area of the surface protruding from the water**
To be effective, the surface that remains above the water must be at least approximately 3 x 5 meters (Dijkstra V. , Hoogwatervluchtplaatsen (HVP), 2021). A smaller area would be insufficient for the burrowing requirements of a beaver family. Moreover, this area should be planted over with shrubs (for example hawthorn), to create stability and cover.

iv. **Substrate**
By using heavy clay, an HVP with a steeper slope can be constructed, which reduces backwater build-up. In addition, heavy clay prevents badgers from taking the HVP as a den site as they prefer to burrow in well-drained soils (Dassenburchten, 2022). Beavers prefer clay soils as they can build their dens close to a water channel with low risk of collapse.

v. **Location and tranquillity**

The HVP should be situated such that recreationists and dogs do not cause a disturbance. This would discourage the settlement of beavers in the installation location.

vi. **Orientation relative to water currents**

By placing the HVP in a low-current location, turbulence is reduced. This may include locations in riparian forests or other woody vegetation, or downstream of a bridge pier.

vii. **Coverage and stability**

By covering the HVP in thorny bushes such as hawthorn, a dense cover is created that provides peace and shelter for the beavers. In addition, the roots stabilize the soil body and the burrows dug in it. This stability ensures less maintenance is required for the HVP.

viii. **Grazing areas**

The HVP should be located away from areas used for grazing. If not possible, the HVP should be fenced off to prevent damage by grazing livestock.

#### *2.6.2. Floating HVP*

Divergent from the grounded concepts made so far of beaver refuges, floating high-water refuges are now also under investigation. The idea is to design a structure that remains in the same position but can move up and down with the rising or falling of water levels. Between 1970 and 1980 in Germany, a preliminary concept made of wooden pallets anchored by chains was tested. Beavers occasionally used the structure but due to issues with stability (V. Dijkstra, 2021) pertaining to the low weight of the structure, the beavers preferred to burrow in adjacent banks and flood defences. In addition, the pallets offered no shelter from the elements.

An example of a cabin concept that addresses those concerns is given in Figure 9 below.

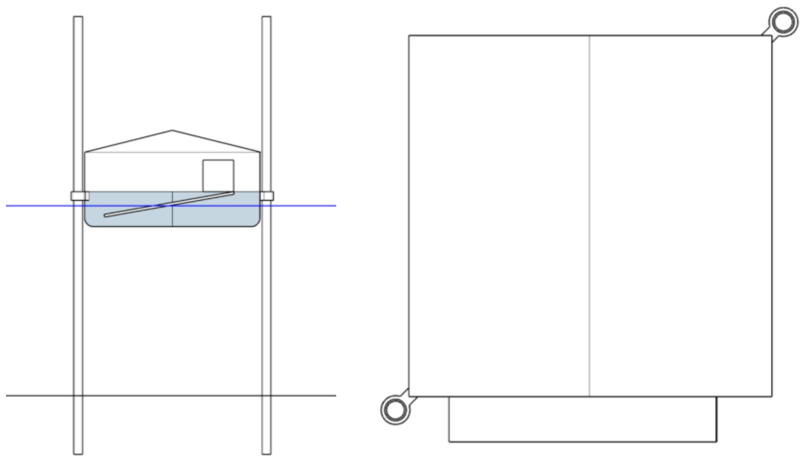


*Figure 9: floating HVP concept*
*(Source: concept of Vilmar Dijkstra, Zoogdiervereniging)*

The fact that the pallets were sometimes used by the beavers and that during a high tide floating logs are occasionally used, gave the inspiration to further elaborate on the idea of floating HVPs. This has the benefit over soil body HVPs that they can be used without excessive obstruction of water flow and therefore is not as intrusive in the location of installation.

### *2.6.3. HVP constructed against the flood defence*

An additional alternative could also be to set up a structure against the dyke, but completely outside its profile. This could include installing a compartment that is shielded from the rest of the barrier by using steel sheet piles. They would be installed in a U-shape, protected from the back and sides, and only opening out to the waterfront. By constructing it against the dyke instead of within, the stability of the dyke is not compromised.

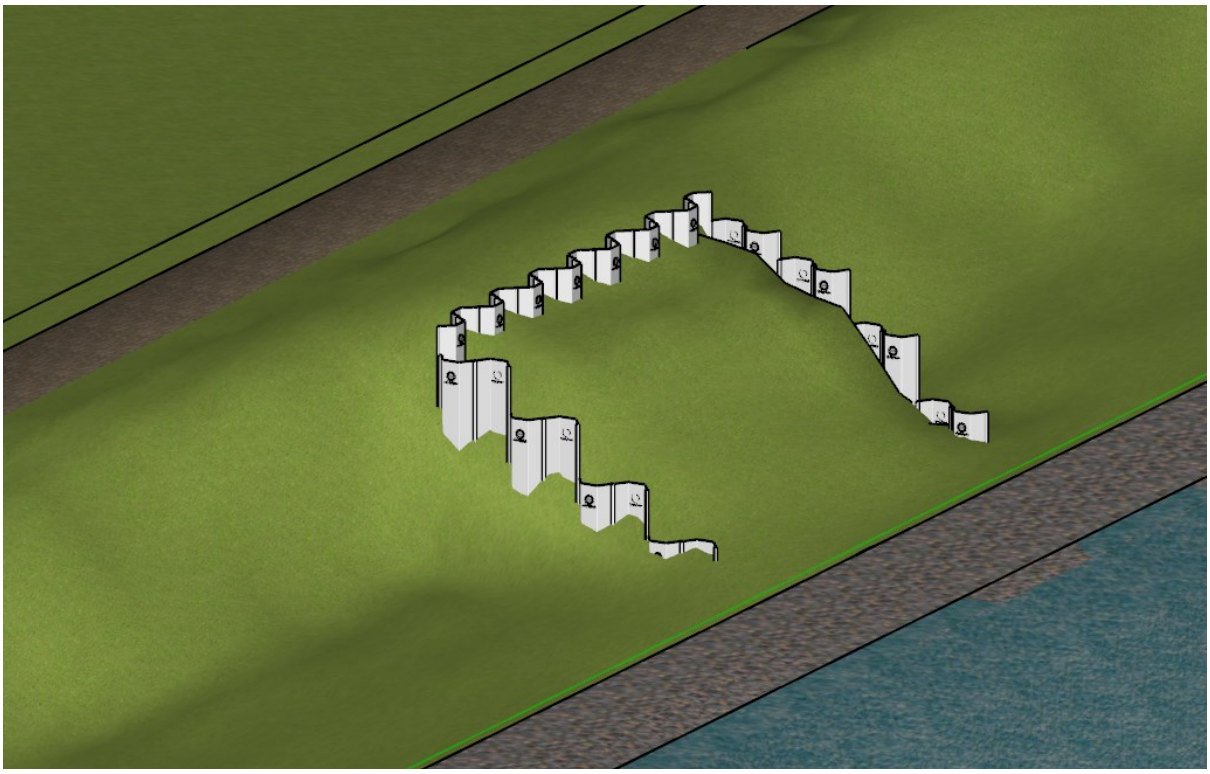


*Figure 10: use of sheet pile compartment placed against dyke*

This compartment could be made more attractive to beavers through the installation of shrubs and bushes and should be fenced off to prevent disturbances by dogs and people. Finally, to ensure use by beavers alone, the fill material should be heavy clay, as badgers prefer sandy soils (Dijkstra & Popelier, Bever & Das in Meanderende Maas, 2021).

## 2.7. Floating structures

Much of the information used in this report alludes directly or indirectly to the considerations used in the construction of floating docks. This is due to the fact that they are similarly sized floating structures that face much the same conditions and loads as are expected on the floating high-water refuges. As such, the methods and considerations used in their design are presented here.

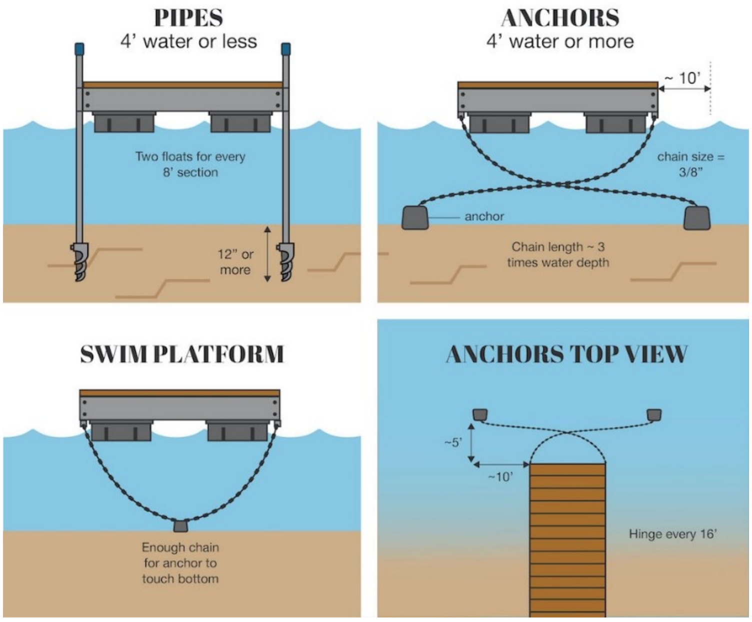



*Figure 11: floating dock anchorage systems (Source: JackDocks)*

A floating dock, pier or jetty is a platform or ramp buoyed by pontoons and typically held in place by vertical poles anchored in the bed or floor of a waterbody. They may also be anchored by chains, cables and winches or elastic anchors. These structures are designed to function as access gangways on waterways that experience low and high-water seasons, hence the vertical accommodation despite being restricted laterally. They are made to withstand harsh loading conditions such as high and low floods and meet stringent requirements for structure, function, and safety. This is therefore used as a starting basis for the development of floating high-water refuges.

The basic elements of such structures are the base frame, the deck, the pontoons or floats, and the anchorage mechanism. The materials typically used to construct these are presented by the MCA in Chapter 5.1. They are generally lightweight and durable materials that resist decay, corrosion, water absorption, and boring insects. The walls of the final design proposed by this research paper are composed of the same material used in the base platform, and the roof of composite lightweight material.

## 2.8. Hydrostatic principles

While standing on a floating structure, one may take for granted that it will float the right way up. This it will only do if it is correctly designed. Furthermore, in service it will experience many forces (e.g., from wind and waves) which may potentially turn it over. It must be capable of resisting these by what is termed its stability. Too much stability is undesirable because it can increase the frequency of oscillations (and reduce their period) to the point of discomfort (does not apply to small/lightweight structures)

Thus, as with so many other design features, stability is a compromise. Because a floating structure will meet varied conditions during its life, stability standards should be set accordingly. No floating structure can be guaranteed stability under all conditions.

The static stability of a floating structure encompasses the righting properties of the structure when it is brought out of its state of equilibrium by a disturbance to its force and/or moment of equilibrium. As a result of these loads, the structure will translate linearly and/or rotate about its centre of gravity in six different ways, outlined in the diagrams below:

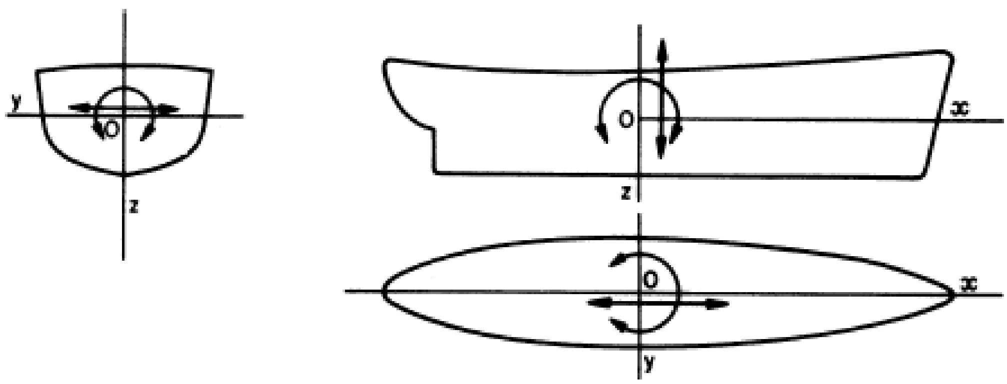



*Figure 12: rigid body movements*

Translations:

- In the x-direction, this is called surge
- In the y-direction, this is called sway
- In the z-direction, this is called heave

Rotations:

- Around the x-axis, it is called roll
- Around the y-axis, it is called pitch
- Around the z-axis, it is called yaw

### 2.8.1. Archimedes' law

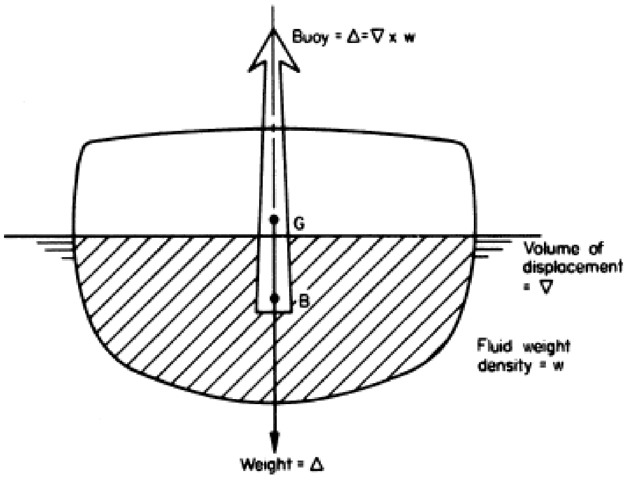



*Figure 13: overview of hydrostatic points*

This is a physical law of buoyancy discovered by the ancient Greek mathematician and inventor Archimedes. As per the Encyclopaedia Britannica, it states:

> *Any object, wholly or partially immersed in a fluid, is buoyed up by a force equal to the weight of the fluid displaced by the object.*

When at equilibrium, the body experiences an upthrust equal in magnitude to the weight of the fluid displaced, which is also equal to the weight of the floating body. This upward-acting force is called buoyancy. In addition, the volume of displaced fluid is equivalent to the volume of the submerged volume of the object.

$$F_A = \rho g V$$

Where:

| | |
|---|---|
| $F_A$ = Buoyant force | [N] |
| $\rho$ = Density of fluid | [kg/m$^3$] |
| $g$ = Gravitational acceleration | [m/s$^2$] |
| $V$ = Volume of displaced fluid | [m$^3$] |

The body will float if its aggregate weight density is less than that of fluid. If it has the same aggregate weight density as the fluid, the body will appear to be weightless in the fluid. Finally, if the aggregate weight density is higher than that of the fluid, it will sink.

The immersed or submerged body experiences all of the hydrostatic pressures present in the fluid before displacement (Rawson & Tupper, 2001).

### 2.8.2. Hydrostatic pressure

Archimedes' principle is based on the principle of hydrostatic pressure. In a fluid at rest, the pressure acts in equal magnitude in all directions of the same plane of submersion. In a fast-flowing fluid, this law does not hold up. However, in fluids that are flowing slower, the differences are negligible (Koekoek, 2010). This bodes well for the calculations required for this design process, as the installation site will be in a sheltered section of the Meuse (Dutch: Maas).

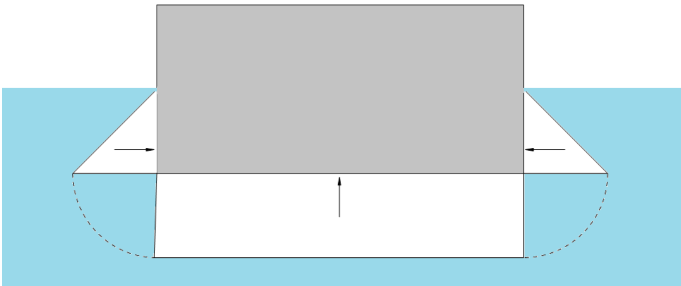


*Figure 14: water pressure overview*
*(Source: own drawing)*

The hydrostatic pressure is proportional to the depth of the fluid, its density, and gravitational acceleration. The water pressure acting on the sides of the immersed body, as shown in Figure 14, results in the net upward buoyant force.

$$p = \rho g z$$

Where:

$p =$ Water pressure [Pa]

$\rho =$ Density of fluid [kg/m$^3$]

$g =$ Gravitational acceleration [m/s$^2$]

$z =$ Depth of submersion/immersion [m$^3$]

The horizontal forces from fluid pressure in the figure are in equilibrium on both sides, hence no horizontal displacement. The weight of the structure is counteracted by the vertical water pressure to create equilibrium, with no further immersion nor buoying.

$$F_H = \rho_w g d * 0{,}5 d l$$

$$F_V = \rho_w g d * b l$$

Where:

$d =$ Draught of floating body [m]

$l =$ Length of body [m]

$b =$ Width of floating body [m]

The scheme shown below will be useful for this analysis. It depicts a buoyant body and a superstructure, which is a simplified model of the designs made for this research. The shared centre of gravity is labelled G, and the centre of buoyancy, B, is the centre of gravity of the displaced water, hence the centroid of the buoyant force.

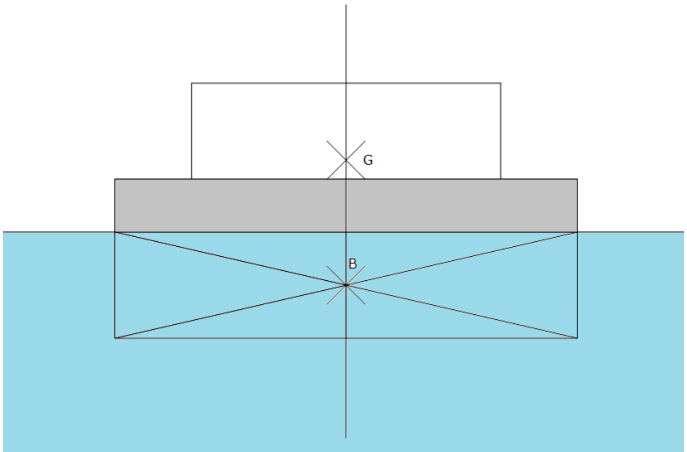
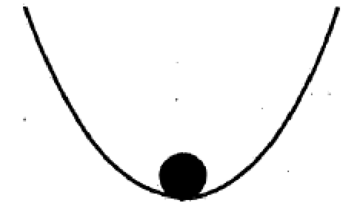



*Figure 15: simplified scheme*

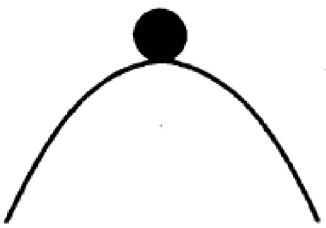
### 2.8.3. Stability

A floating structure is said to be in a state of equilibrium when the resultant of all the forces acting on it is zero and the resulting moment of these forces is also zero (Journée, 1997).



If the structure, subject to a small disturbance from a position of equilibrium, tends to return to this state it is said to be in a state of stable equilibrium or to possess positive stability.

If, following the disturbance, the structure remains in its new position, then it is said to be in a state of neutral equilibrium or ta possess neutral stability



If, following the disturbance, the excursion from the equilibrium position tends to increase, the structure is said to be in a state of unstable equilibrium or to possess negative stability.

### 2.8.4. Tilt

This is defined as the rotation induced on a structure by the moment caused by an external eccentric load, such as wind, waves, etc.

The result of this moment is a change in the water pressure experienced by the immersed body. Due to the rotation, the submerged cross-section changes in shape, resulting in an uneven distribution of water pressure across the hull. This in turn causes a moment, aptly called the righting moment, which acts in the opposite direction of the acting moment to neutralise the motion and return the structure to equilibrium. This has the lever arm GZ.

In addition, due to the change in the submerged cross-section, the centre of buoyancy shifts from $B_0$ to $B_1$ on a line parallel to the line through the centres of the emerged and immersed wedges.

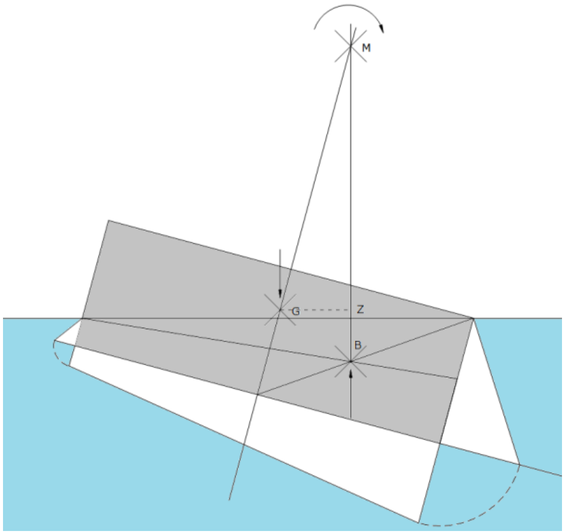



*Figure 16: acting moment and pressure differential*

If the centre of gravity is situated near the centre of buoyancy (as is the case here in a symmetrical floating body of low height), the rotation will be small, and the righting moment can be calculated via the following formula:

$$M_{righting} = \varphi \rho g I_t = F_A * GZ$$

Where:

$\varphi$ = Rotation [°]
$I_t$ = Transverse moment of inertia [$m^4$]
$GZ$ = Righting arm [m]

In order to maintain equilibrium, this righting moment should be equal to the acting moment. If not, capsizing will occur. This expression therefore applies:

$$M_{acting} = M_{righting}$$

If the righting moment can return the floating body to its original position, the floating structure is stable.

In the case that a load is imposed on the structure, it will lead to a slight subsidence (increased main draught) and a tilt. This subsidence is a result of a shift in the centres of gravity and buoyancy toward the position of the imposed load. This is because the mass of the system changes along with its mass distribution. Moreover, the centre of buoyancy shifts due to increased volume of displacement and a change in the submerged shape of the floating body.

These two shifts can be calculated using the following four formulae [for 2-dimensional translations] (Journée, 1997):

$$G_0G_{1;\,horizontal} = \frac{a * m}{\rho . V_0 + m}$$

$$B_0B_{1;\,horizontal} = \frac{a * m}{\rho . V_0 + m}$$

$$G_0G_{1;\,vertical} = \frac{(GO + b) * m}{\rho . V_0 + m}$$

$$B_0B_{1;\,vertical} = \frac{\left(BO + \left(\frac{d}{2}\right)\right) * m}{\rho . V_0 + m}$$

Where:

| | | |
|---|---|---|
| $a$ = | Horizontal distance to imposed load from origin | [m] |
| $b$ = | Horizontal distance to imposed load from origin | [m] |
| $m$ = | Added mass | [kg] |
| $V_0$ = | Initial volume of displaced fluid | [m$^3$] |
| $\rho$ = | Unit weight of fluid | [kg/m$^3$] |
| $d$ = | Increased draught | [m] |

Moreover, the rotation of the structure due to the imposed load can be calculated using the following formulae, whose parameters are elaborated further in the subsequent pages addressing the metacentric height.

$$\sin\varphi = \frac{M_{acting}}{F . MG}$$

$$\sin\varphi = \frac{G_0G_{1;\,horizontal}}{MG_0}$$

### 2.8.5. Metacentre

The metacentre is the point of intersection of the lines through the vertical buoyant forces at an angle of heel zero and at an angle of heel $\varphi$ (Journée, 1997). In other words, it is where the line of action of the net buoyant force and the centreline of the structure meet.

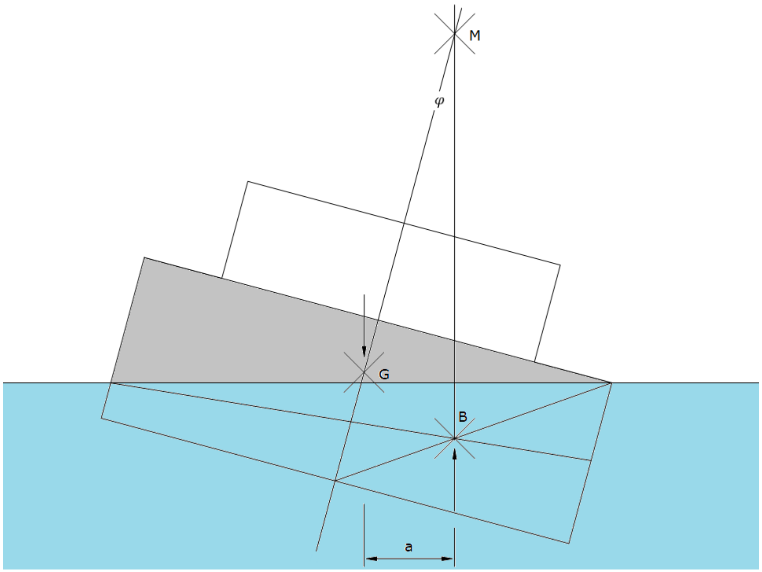



*Figure 17: intersection of centreline and buoyant line of action*

Consequently, this gives rise to the metacentric height (GM), which is a measurement of the initial static stability of a floating body. It is calculated as the distance between the centre of gravity of a ship and its metacentre. A larger metacentric height implies greater initial stability against overturning. The metacentric height also influences the natural period of rolling of a hull, with very large metacentric heights being associated with shorter periods of roll which are uncomfortable for passengers.

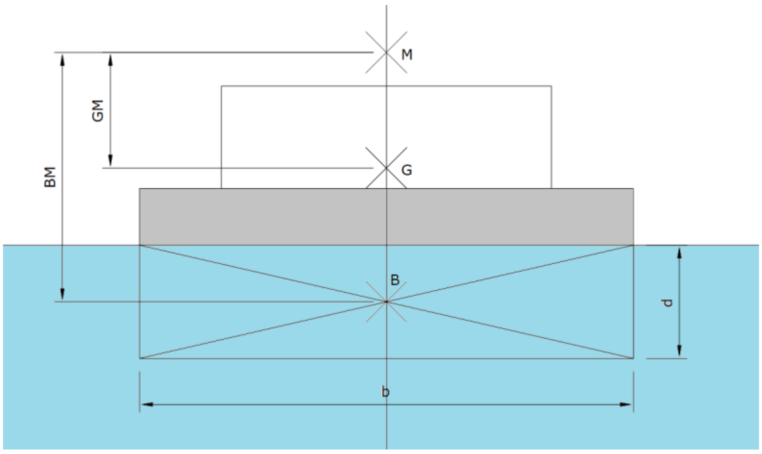



*Figure 18: metacentre and metacentric height*

The position of the metacentre is the determining factor for the stability of the structure. If it is located above the centre of gravity of the structure, then a righting moment will restore the stability should an external moment cause a rotation. Should the metacentre be located below the centre of gravity, then a heeling moment will arise, causing tilting and ultimately capsizing. With that in mind, it is clear that the metacentre should always be positioned above the centre of gravity if stable upright equilibrium is to be attained. The larger the distance between, the greater the stability.

A floating structure is said to be wall-sided if, for the angles of heel to be considered, those portions of the outer bottom covered or uncovered by the moving water plane are vertical with the structure upright, as is the case for the designs made within this research.

For such structures where the emerged and immersed wedges are described by right-angle triangles, the Scribanti formula describes the distance between the metacentre and the centre of buoyancy by the following expression:

$$\mathrm{MB} = \frac{\mathrm{I_t}}{\mathrm{V}} * \left(1 + \frac{1}{2}\tan^2\varphi\right)$$

$$MG = OB + MB - OG$$

Where:

| | |
|---|---|
| $I_t$ = Transverse moment of inertia of the water plane | [$m^4$] |
| $V$ = Volume of displaced fluid | [$m^3$] |
| $\varphi$ = Rotation | [°] |
| $MB$ = Distance between metacentre and centre of buoyancy | [m] |
| $MG$ = Distance between metacentre and centre of gravity | [m] |
| $OB$ = Height of centre of buoyancy from origin/centre of keel | [m] |
| $OG$ = Height of centre of gravity from origin/centre of keel[m] | |

From this formula, it is evident that the position of the metacentre is partly dependent on the angle of rotation. This influence is negligible for smaller rotations (<10°). This the gives the simplified formula:

$$MB = \frac{I_t}{V}$$

For a floating body with a rectangular cross-sectional shape, the values of I and V are as follows:

$$I_{t,rect} = \frac{1}{12} * lb^3$$

$$V = lbd$$

Combining the above three formulae gives:

$$MB = \frac{b^2}{12d}$$

Evidently, the formula above will give different results for the two axes of the floating body if the length and width are unequal. The normative direction for stability will be the narrower side, and so this should always be analysed first.

The height of the point of buoyancy from the underside or keel of the floating body is half the draught for a rectangular cross-section.

$$OB = \frac{d}{2}$$

$$\therefore OM = OB + MB = \frac{d}{2} + \frac{b^2}{12d}$$

Finally, the value for the metacentric height (distance between the metacentre and centre of gravity) can be attained via the following formula:

$$MG = OM - OG = \frac{d}{2} + \frac{b^2}{12d} - OG$$

#### 2.8.6. Wave forces

Horizontally, the forces are manifested by differences in wave height for non-breaking waves and through impact forces resulting from breaking waves. For this research, only the former will be addressed as the conditions at the expected installation location experience few to no breaking waves.

For the non-breaking waves, the forces are caused by a difference in water height between the upstream and downstream sides of the floating structure. This difference in water height results in a water pressure difference that ultimately exerts a force on the structure, explained by the following standard method (assuming waves on only one side):

$$F_{max} = \frac{1}{2}\rho g H_i^2 + d\rho g H_i$$

Where:

$F_{max}$ = Maximum horizontal force per metre [N/m]

$H_i$ = Height of incoming wave [m]

$d$ = Draught of floating structure $= d_t + H_i$ [m]

These variables are depicted in Figure 19.

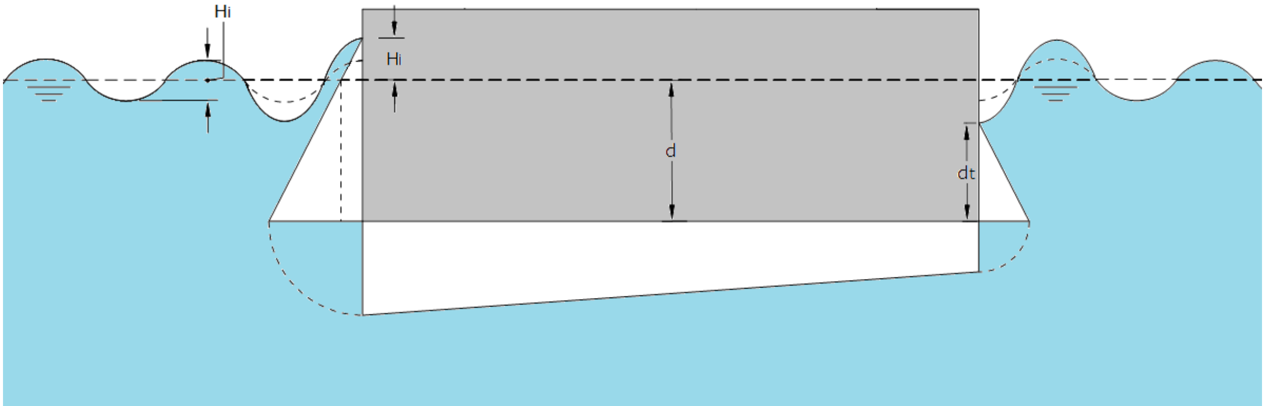



*Figure 19: horizontal pressure gradient formed by incident waves*
*(Source: own drawing)*

$H_i$ is the height of the incoming waves. According to the linear theory for non-breaking waves against a vertical wall, the wave height H (crest to trough) in front of the structure is double the incoming wave height $H_i$, in the case of total reflection (Koekoek, 2010). The trough formed on the other side of the structure adds to the total horizontal force as the pressure gradient is even larger, depicted by the white trapezium below the floating body.

The formula is therefore altered to accommodate this situation:

$$F_{max} = \frac{1}{2}\rho g(2H_i)^2 + d_t\rho g(2H_i)$$

Where:

$F_{max}$ = Maximum horizontal force per metre [N/m]

$H_i$ = Height of incoming wave [m]

$d_t$ = Draught in wave trough [m]

## 3. List of design requirements

The following requirements stem from consultation with professionals from the Zoogdiervereniging and the waterboards Aa en Maas and Rivierenland. They outline the conditions needed to be satisfied by the design, and as such guide the design process.

The technical requirements provide details that allow the implementation of a structurally sound design. They comprise the following:

- The high-water refuge should offer stability even during storm conditions – turbulent or rushing water. This will be the predominant condition in the locations of installation, as the floating HVPs will be used where soil body HVPs cannot be used due to the risk of obstruction of flow.
- The stretch of water in which the structure is to be installed must be examined to determine the maximum possible fetch and therefore resultant waves.
- The choice of material should:
    i. Be resistant to weathering by the elements. This prolongs the lifespan of the structure and minimises the need for maintenance.
    ii. Offer adequate insulating properties against the cold while still allowing adequate ventilation.
    iii. Be of low environmental consequence. The overall effect on the environment throughout the materials' lifespans is considered here, in addition to the feasibility of reuse or recycling.
    iv. Be of low cost. This allows for more structures to be installed and therefore monitored for actual use.
- The design should facilitate maintenance and cleaning.
- The maximum buoyancy of the structure should be greater than the maximum expected load.
- Accommodation should be made for wildlife monitoring cameras, one on the exterior (providing coverage of ramp and entrance) and another in the interior. Access should be provided for installation and maintenance.
- The structure should be designed such that it may be easily transported to the installation sites, either in whole or in components (prefabricated design).
- The high-water refuge should be placed in a calm/slower section of the water channel, despite allowing for more extreme flows. This limits the load on the structure to minimise maintenance requirements and prolong lifespan.
- The refuge design should aim to minimise vulnerability to large floating debris during a flood such as trees or logs which may act as a battering ram on the structure. Provisions for this may be to make the structure as compact as stability allows in order to limit exposed surface area; to allow free movement so that the structure can move out of the way rather than be sandwiched and crushed; or to use a protective mechanism that deflects such debris.

The functional requirements are the drivers of habitat selection as they make provisions for the intended users of a design. These may include the position of the structure within the landscape, its orientation, physical dimensions, colour, microclimate dynamics, structural complexity, hardness, porosity, surface chemistry, and many more.

For the design of floating high-water refuges for beavers, these are relevant:

- The materials chosen for the refuge should not encourage gnawing by beavers. Indeed, they should not be repellent to beavers either.
- Waves should not be able to enter the structure – the floor should not be wetted. The purpose of a high-water refuge is to provide beavers with a dry resting place during high river discharges. If the animals stay in the water for too long, they become hypothermic. Depending on the duration and severity of the hypothermia, this has negative consequences for the condition of the animals, possibly resulting in death (Dijkstra V. , 2017).
- Installation locations should be dependent on active beaver sites or current habitats. These may be found through the beaver and badger activity survey made by V. Dijkstra and T. Popelier (Bever & Das in Meanderende Maas, 2021)
- A sufficiently calm area away from human activity (e.g., dog-walkers) should be chosen for the installation of the refuge.
- The dimensions should be such that a beaver family can use the structure comfortably:
    i. The main entrance shall be 35 cm*35 cm. This allows for easy entrance and egress from the structure.
    ii. A rear opening or exit hole should be provided to allow intruding animals (otters, other beavers, birds) to escape without conflict. The dimensions for this are to be 25 cm*25 cm, which provides ample space for these smaller animals to escape. For example, Eurasian otters can squeeze through a gap of minimum 12 cm. It is believed that this exit hole would be blocked off by the beavers when the structure is in use (Dijkstra V. , HVP Evaluation Criteria, 2022).
    iii. The inner dimensions of the structure shall be 2m*2m. This provides adequate space for a large beaver family of 8, consisting of 2 adults and 3 consecutive litters of 2 kits each (Dijkstra V. , HVP Analysis Criteria, 2022). The average family consists of 4.5 animals (Dijkstra V. , Omgaan met de bever, 2020).
    iv. As established in consultation with professionals from the Zoogdiervereniging, the inner height of the structure at the lowest point should be 40 cm.
    v. The structure will be accessed from the water using a ramp of minimum 25 cm width.

# 4. Methodology

Here, the planned approach to answering the various research questions shall be laid out. This is done to ascertain the validity of the data obtained and allow replication of results.

The primary research question is:

*What refuge design is the most viable?*

To answer this, the following secondary questions are drawn up:

**1. What is the most optimal choice of materials and components?**

A multi-criteria analysis (MCA) shall be used to assess the behaviour of a selection of materials and components in relation to desired properties of the final structure. These elements shall be compiled such that, in coordination with the calculation results, a final design is produced.

The analysis shall use criteria which are based on consultation with experts in the field of beaver behaviour (Zoogdiervereniging) and water safety (Waterschap Aa en Maas), as well as literature review of beaver behaviour and animal enclosure management.

This is addressed under Chapter 5.1. Multi-criteria Analysis.

After installation, the structures shall be monitored (not within the scope of this thesis) to document actual use by the beavers to optimise elements of their design should the need present itself.

**2. Where should the structure be built?**

The chosen area of analysis is the Meanderende Maas project area. Most importantly, this is because it is an area that accommodates several beaver territories. However, the project vision also ties in with the ideal outcome of this research: to protect the dykes as well and to maintain harmony with nature (by providing compensation and/or mitigation measures). Moreover, the project lies partly within the jurisdiction of the Waterschap Aa en Maas.

To ascertain viable locations of installation within this area, various criteria are analysed to determine the most suitable locations. Maps of different data sets were used to do this. These show the active beaver sites within the area, the major landholders, the topography, and the river conditions of the area. These shall be evaluated to determine their relative influence over the installation site.

This is further addressed in Chapter 5.2. Location Analysis.

**3. Will the structure withstand the expected loads?**

Appropriate deck loads (beavers) and their distributions are accounted for in order to determine sufficient buoyancy and stability in zero flow conditions (hydrostatic stability). Beyond this, the conditions at the chosen installation location(s) are analysed and translated into forces applied to the structure to ensure stability when subjected to waves.

This is addressed in Chapter 8. Results and discussion.

# 5. Analyses

## 5.1. Multi-criteria Analysis

A multi-criteria analysis is a structured approach used to compare different alternatives in order to determine the most appropriate. It is especially used where multiple conflicting criteria accomplish several objectives, in a way that a simple cost-benefit analysis would fall short in evaluating as environmental or social impacts cannot be easily quantified and monetised (Infrastructure Australia, 2021), as is the case in this research. It aids in filtering the list of options down to a smaller number for a more detailed analysis.

The method used for this is to identify the most valuable criteria or measures that would aid in satisfying the established objective, which in this case refers to answering the primary research question.

*What refuge design is the most viable?*

These criteria are then accorded weights (percentages) as per their relative importance to the element in assessment. The chosen weights are then scored against the element, depending on the properties of the element in relation to the selected criteria.

To break this down simply and intuitively, the following scoring system shall be used in this assessment.

| SCORE | RATING | DESCRIPTION |
|---|---|---|
| **5** | Strong positive | Strong, positive impact for the criterion |
| **4** | Moderate positive | Moderate, positive impact for the criterion |
| **3** | No significant impact | No significant positive or negative impact |
| **2** | Moderate negative | Moderate, negative impact for the criterion |
| **1** | Strong negative | Strong, negative impact for the criterion |

To answer the established research question, it is necessary to assess a number of elements that each bear on the final design's ability to successfully house a family of beavers during a high-water period and therefore ultimately protect the dyke from burrowing.

The elements evaluated are broken into three main groups, resulting in 3 different MCAs. This is done because each element serves a different purpose and therefore cannot be assessed via the same selection of criteria and/or criteria weights. For each of these element groups, various alternatives are proposed. Namely, these groups are:

i. Anchorage mechanism – the anchorage ensures the structure remains in a given location and may also be used to provide stability.
ii. Material choice – the materials used in construction shall determine the liveability and longevity of the structure, among other considerations.
iii. Entrance type – beaver dens typically have an underwater entrance, resulting in minimal ventilation and few intruders. The benefit of replication is therefore assessed.

The design concept for the body of the main structure will be based on pragmatic considerations arising from the selection of optimal elements. This is addressed further under Chapter 7. Concept design. The dimensions of this final main structure shall be optimised by the results of the stability equations presented in Chapter 8. Results and discussion, which are worked out in Appendix D. Stability calculations.

#### *5.1.1. Criteria*

As explained, three different lists of criteria are used, one for each of the aforementioned elements. The list of criteria below shall be used for the analysis, with varying criterion weights per analysed element to represent the **relative order of importance** of the criterion per element to the floating refuge as a whole.

| ELEMENT | CRITERION | WEIGHT |
|---|---|---|
| **Anchorage mechanism** | Stability | 0,35 |
| | Vulnerability | 0,30 |
| | Durability | 0,15 |
| | Complexity | 0,10 |
| | Cost | 0,10 |
| **Material choice** | Heat retention | 0,20 |
| | Environmental impact | 0,25 |
| | Durability | 0,30 |
| | Colour | 0,10 |
| | Cost | 0,15 |
| **Entrance type** | Heat retention | 0,25 |
| | Complexity | 0,20 |
| | Durability | 0,20 |
| | Conflict | 0,15 |
| | Cost | 0,20 |

Each of the criteria has been accorded a different weight based on in-company consultations with involved and experienced specialists in the domains of water safety and mammal behaviour. The professionals in consultation are namely:

- **Ronald Wolters** – Flood Risk Management Policy Advisor, Waterschap Aa en Maas
- **Vilmar Dijkstra** – Senior Project Collaborator, Zoogdiervereniging

The criteria from the table above are further explained as follows:

**1. Stability**

This is an important criterion in that the structure's primary purpose is to offer shelter during high-water periods and therefore ultimately protect the flood defences. As such, it must be able to withstand the waves that are associated with extreme discharges. This is evaluated outside of the free body calculations to determine the additional stability provided by the anchorage mechanism.

**2. Vulnerability**

The quality of being exposed to damage caused by impact with floating debris, such as trees, logs, and artificial paraphernalia. This correlates with the total amount of space taken up by the element at the installation site. A better score is awarded to components that use less area as this limits the probability of being struck by said floating debris.

3. **Durability**

Here, the maintenance requirements of different components, the wear and erosion of materials, the number of moving parts, as well as the strain experienced by non-moving parts, are evaluated.

4. **Complexity**

The assemblage of different components will have different scores relating to the difficulties expected to be faced in procurement, transportation, assembly, and installation. The simpler the component is, the more favourably it will score.

5. **Cost**

This refers to the total amount of capital spent on procuring all the products, services, and resources needed to bring the project to completion. Without adequate monitoring and controlling of the funds available, the project may not be completed according to schedule or up to the desired quality. Moreover, lower overall cost means more pilot structures may be installed to monitor their de facto performance.

6. **Insulation**

The ability of the various components to provide heat retention in the main body of the structure. This can be through the minimisation of conduction, convection, or radiation of heat out of the refuge.

7. **Environmental impact**

The materials used for the construction of the refuge will have varied rates of decomposition and/or breakdown. The effect this breakaway material has on the environment after being washed away by the river is analysed.

8. **Colour**

The colour of the structure may have influence over the acceptance by the beavers of the structure, through its ability to blend in with the surroundings and keep from being spotted too easily by would-be predators or human vandals. In addition, the colour should not contrast starkly with the surrounding area in order to maintain the natural aesthetic of the project coordinators (Meanderende Maas). Lastly, the ability to retain and absorb heat will partly depend on the colour of the structure.

9. **Interspecific conflict**

The refuge may end up being attractive to more than just the target species. Ducks, otters, coots, and other animals may use the structure in the absence of the beaver(s), whose intrusion may cause conflict between the animals. Hence, ideas have been proposed among the variants that aim to limit this possibility.

### 5.1.2. Alternatives

In order to fulfil the technical and functional requirements listed in Chapter 3: List of design requirements, specific materials and components are proposed, each of which would serve in a different capacity to attain those properties. These options fall under the 3 main groups of design elements from the preceding sub-chapter, namely: the anchorage mechanism, the materials used for the floating body of the refuge, and the type of entrance.

1. **Anchoring mechanism** (explanatory models and pictures may be found in Appendix E: Anchorage mechanisms)**:**
   - Screwed poles (FLOE International, 2013):

     These will be fixed to the platform via a socket/sleeve, which will allow for vertical motion while remaining fixed laterally. The poles are threaded (like an auger or screw) at the bottom in order to allow fixation in the channel bed.
   - Telescopic poles:

     This concept was proposed through a meeting with the core HVP research group, which consists of professionals from the Zoogdiervereniging, Waterschap Aa en Maas and Waterschap Rivierenland.

     The supports would each be constructed out of three large hollow poles that fit into one another by means of their decreasing diameters and are locked into place such that only movement up and down is allowed. These poles will be anchored into the bed by use of a steel plate embedded in the soil.
   - Stiff arm (Stiff Arm Dock System, 2017):

     This is a rigid metal frame that is connected via hinges on one end to a floating platform (typically a small landing or jetty) and on the other to a fixed point on the bank of a water body. This acts to restrict the motion of the floating platform. One stiff-arm provides stability along one plane of tilt, whereas the use of two would ensure stability along two planes and therefore only allow motion vertically. The use of only one shall be investigated in the MCA.
   - Weighted rope (Stangland, 2019):

     Two ropes would be tied to the bottom of the floating structure, and on the other end, to concrete blocks on the channel bed that serve as anchors. In addition, smaller concrete blocks would be suspended at intervals to provide tension irrespective of the water level. The weight of the suspended ropes and the resistance of the anchors minimise lateral movement. The ropes would limit the structure to drifting around the anchoring points in a specified radius (depending on water level and rope length).
   - Wooden pile and collar:

     This is another concept proposed through a meeting with the core HVP research group. It would be an anchored post around which the structure could freely rotate through a collar connection between a corner of the floating refuge and the pile. The pile would be anchored in the bed of the channel with a concrete block, and on the other end at the top, a stork's nest could be constructed as an additional compensation measure. Moreover, as a recommendation from a professional at Rijkswaterstaat, a pile of rocks could be placed at the bed level of the pile to reduce scour erosion of the soil around it.

2. **Material choice** (reference pictures may be found in Appendix F: Materials)**:**
   - Floats:
     - Plastic barrels – reused storage barrels sourced from industry or domestic users. May be procured from Marktplaats, for example.
     - Reinforced EPS blocks – these are simply blocks of expanded polystyrene (Styrofoam) which are reinforced by a coat of glass fibre that is held together by cement mortar. These may be purchased from a local jetty and dock solution company such as Inter Boat Marinas in Puttershoek, or simply constructed through a DIY delineation.
     - Modular dock floats – these are sealed plastic containers that can be bought from dock solution retailers. They have the advantages of being easily connected, resistance to UV ray disintegration, and the ability to withstand collision through robust design. They may also be sourced locally, such as through Dock Parts, a company based in Veersedijk.
   - Roof:
     - Corrugated fibre cement sheets – these are crafted from a reinforced composite material that is formed into a corrugated profile to provide outstanding durability. Moreover, the material is vapour permeable and has a moisture-buffering capacity, so condensation is minimised (Dak Renoveren, 2022). The sound-damping properties are another advantage in that the noise nuisance that is synonymous with thin corrugated roofing sheets is minimised. This is favourable for beaver acceptance of the floating refuge as their natural dens are also relatively sound-proofed.
     - Hydro-thermally modified wooden panels – Platowood is a Dutch company that uses sustainable methods to treat softwood boards. The patented process (dubbed "platonising") is carried out in-house in Arnhem and consists of three important steps: hydro-thermolysis, drying and curing. This unique technology only requires water and heat. No chemicals are added, as opposed to mainstream methods of wood treatment. The resultant material is environmentally friendly, low maintenance, easily processed, moisture resistant and has good insulation value.
     - Corrugated aluminium sheets – these are a popular roofing solution as they are lightweight, durable and have a large strength-to-weight ratio. Nevertheless, the noise produced during rainstorms is unfavourable.

- Insulation:
    - Polyurethane foam – expanding foam that can be used to proof the refuge against heat loss, moisture, sound and (wood-boring) insects. It can be applied in the walls, floor/deck, and roof of the structure (Polyurethaan, 2022). It therefore also prolongs the refuge's lifespan. Additionally, it is inherently more sustainable than most other plastics due to easier recycling and energy-harvesting possibilities.
    - Glass wool – This is an insulating material made from fibres of glass arranged using a binder into a texture similar to wool. The small air pockets result in high thermal insulation properties. It can also be used in the floor, roof, and walls.
- Platform:
    - Hydro-thermally modified wooden boards from Platowood.
    - Recycled plastic panels/boards – these may be sourced from ReFactory, a company from Hull devoted to recycling "harder-to-handle" materials. One of their main products is 'StormBoard', a plastic board designed as a replacement for wooden plyboard. The company has an established office as well as a retailer, Vink Kuntstoffen, in the Netherlands.
- Walls:
    - Hydro-thermally modified wooden panels from Platowood.
    - Recycled plastic panels/StormBoards from ReFactory.

3. **Entrance type** (explanatory roofless models may be found in Appendix G: Entrance types):
    - Open:

      This entrance would be left fully open, allowing easy entry and egress from the structure.
    - Sheltered:

      A narrow corridor would be built adjacent and leading into the main chamber in order to minimise wind chill by keeping the beavers out of direct wind. The exit hole included in the design requirements would lead to the development of a draught through the refuge, but this is expected to be blocked off with twigs and mud during actual use by the beavers (Vilmar Dijkstra, Zoogdiervereniging).
    - Submerged:

      This entrance would be located underwater, leading up to the structure via a tunnel/chute with steps. The purpose would be to keep other species – such as ducks, coots, and otters – from using the refuge, thus limiting interspecific conflicts. An added benefit would be sound and heat isolation. An expected difficulty would be in enticing the beavers into the structure.

The forthcoming criteria, weights and alternatives are compiled and analysed in the table below; the results of which are discussed in Chapter 6: Concept design.

## 5.1.3. Results

| Element | Anchorage | Criterion | | Stability | Vulnerability | Durability | Complexity | Cost | Total |
|---|---|---|---|---|---|---|---|---|---|
| | | **Weight** | | 0,35 | 0,30 | 0,15 | 0,10 | 0,10 | 1,00 |
| | | Screwed poles | | 5 | 2 | 2 | 4 | 4 | 3,45 |
| | | Telescopic poles | | 5 | 2 | 1 | 1 | 2 | 2,80 |
| | | Stiff arm | | 5 | 1 | 1 | 2 | 2 | 2,60 |
| | | Weighted rope | | 3 | 4 | 4 | 5 | 5 | 3,85 |
| | | Wooden pile + collar | | 4 | 4 | 3 | 3 | 2 | 3,55 |
| | **Material** | **Criterion** | | **Insulation** | **Env. impact** | **Durability** | **Colour** | **Cost** | |
| | | **Weight** | | 0,20 | 0,25 | 0,30 | 0,10 | 0,15 | 1,00 |
| | | Floats | Plastic barrels | 3 | 2 | 2 | 3 | 3 | 2,45 |
| | | | Reinforced EPS | 3 | 2 | 4 | 3 | 4 | 3,20 |
| | | | Modular floats | 3 | 3 | 4 | 3 | 2 | 3,15 |
| | | Roof | Fibre cement sheets | 3 | 3 | 4 | 3 | 3 | 3,30 |
| | | | Wooden panels | 3 | 4 | 3 | 3 | 3 | 3,25 |
| | | | Aluminium sheets | 2 | 3 | 4 | 3 | 3 | 3,10 |
| | | Insulation | Polyurethane foam | 5 | 3 | 4 | 3 | 4 | 3,85 |
| | | | Glass wool | 5 | 2 | 4 | 3 | 4 | 3,60 |
| | | Platform | Wooden boards | 4 | 4 | 2 | 3 | 4 | 3,30 |
| | | | Recycled plastic | 4 | 4 | 3 | 3 | 3 | 3,45 |
| | | Walls | Wooden panels | 4 | 4 | 2 | 3 | 4 | 3,30 |
| | | | Recycled plastic | 4 | 4 | 3 | 3 | 3 | 3,45 |
| | **Entrance** | **Criterion** | | **Insulation** | **Complexity** | **Durability** | **Int. conflict** | **Cost** | |
| | | **Weight** | | 0,25 | 0,20 | 0,20 | 0,15 | 0,20 | 1,00 |
| | | Open | | 1 | 5 | 4 | 2 | 5 | 3,35 |
| | | Sheltered | | 3 | 4 | 4 | 2 | 4 | 3,45 |
| | | Submerged | | 5 | 2 | 1 | 4 | 2 | 2,85 |

## 5.2. Location analysis

### 5.2.1. Preliminary selection

The chosen area of analysis is the Meanderende Maas project area. Most importantly, this is because it is an area that accommodates several beaver territories. However, the project vision also ties in with the ideal outcome of this research: to protect the dykes as well and to maintain harmony with nature (by providing compensation and/or mitigation measures). Moreover, the project lies partly within the jurisdiction of the Waterschap Aa en Maas.

New legal safety standards were established in the Water Act on January 1, 2017, making it necessary to adjust the dyke between Ravenstein and Lith. Thus, the Meanderende Maas project was initiated to better protect 270,000 residents and businesses behind the Brabant dyke against flooding during high water in the Meuse (Dutch: Maas).

The project will give the Meuse more space on both sides of Gelderland and Brabant, making the area more attractive and economically stronger. In addition to the Brabant dyke between Ravenstein and Lith, the project area of approximately 2650 hectares also includes the floodplains on both sides of the 18-kilometre Meuse section. The dyke on the north side (province of Gelderland) is safe and is not part of the project (Meanderende Maas, 2017).

High-water refuges (soil body structures as well as floating) are part of the project package, as part of the vision to create an area that is more beautiful and economically stronger with nature, expanding recreational and touristic opportunities in the flood plains. Hence, figures 20 through 23 will be evaluated and compared in order to arrive at the most optimal locations for installation.

The image below (Figure 20) outlines the project boundary, extending more than 18 km from Lith in the west to Ravenstein in the east. Along with the profile of the Meuse, floodplains created from old cut-off meanders are also included:


*Figure 20: overview of study area*
*(Source: meanderendemaas.nl)*

As part of a collection of surveys in the area done in 2021 by Vilmar Dijkstra and Ton Popelier, beaver lodges and dens were located alongside the most vulnerable parts of the flood defences to damage caused by beaver burrowing (Figure 21). These locations provide insight into the most optimal installation sites for the beaver refuges, as greater proximity to active sites is expected to stimulate the successful transition to the high-water refuges. Moreover, installing the refuges close to at-risk dykes minimises the chance that these will be burrowed into.


*Figure 21: beaver activity survey*
*(Source: Bever & Das in Meanderende Maas)*

Furthermore, below (Figure 22) is shown an overview of all the major landholders in the project area, whose permission (in the form of awarded permits and/or exemptions) is required for intervention in the risks caused by beavers. Overlaying this with the last figure shows that beavers are specifically active in areas owned and managed by Natuurmonumenten and Rijkswaterstaat. These will be the stakeholders kept in close contact over regulations surrounding the installation of high-water refuges.

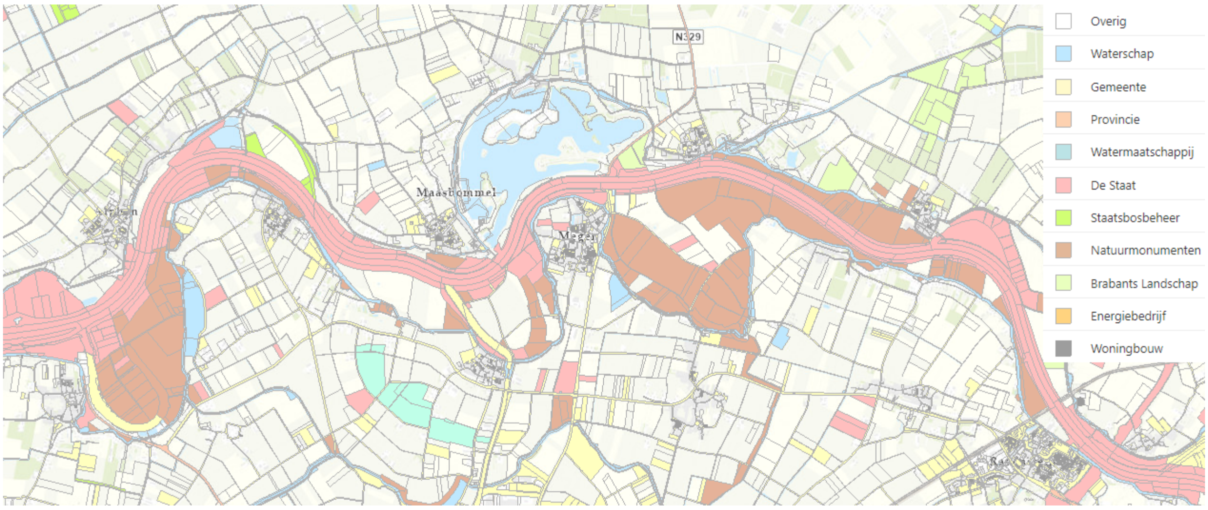



*Figure 22: land parcel ownership and management*
*(Source: webgis.aaenmaas.nl)*

Lastly, shown on the following page (Figure 23) is a layout of the area's topography, ranging from a maximum of 20 metres NAP (red) to a minimum of 3 metres NAP (blue). The topography is an important factor in the installation of high-water refuges, in that the structures must be able to accommodate a worst-case scenario whereby the high-water level is equal to that of the primary dyke. Higher than this level, the river will pour over the dyke and into the polder land.

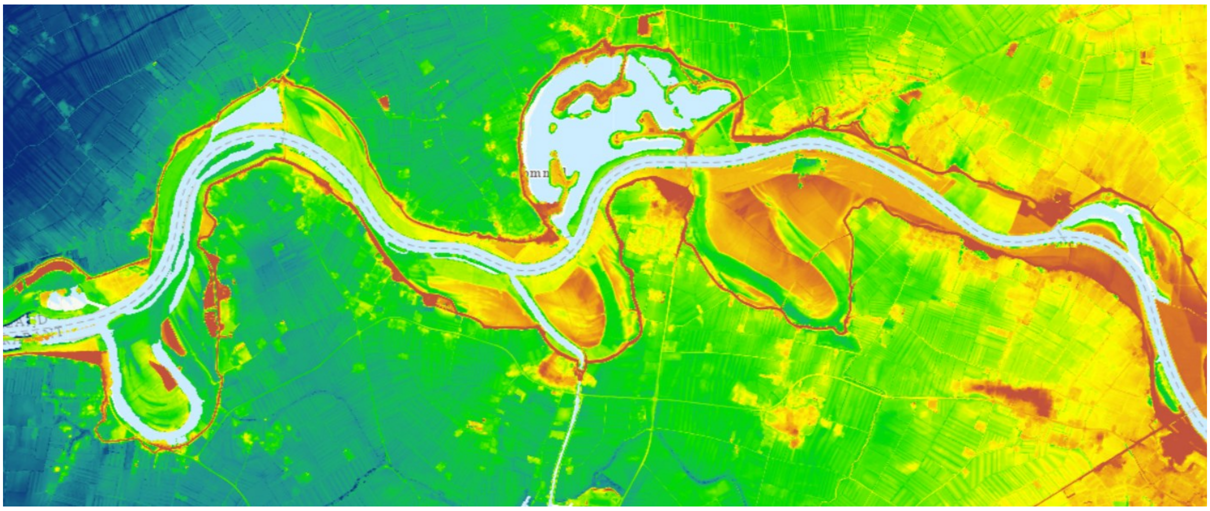


*Figure 23: topography of study area (Source: webgis.aaenmaas.nl)*

As an extension to the above, the river discharge is also lower in the areas with higher elevation due to the obstruction they cause to the flow of the Meuse, hence lowered effects of river flow on the stability and longevity of the structure. This is addressed further under the subsequent heading.

Compiling the above information, one can directly infer that the most attractive areas in which to install the high-water refuges are situated west, east, and north of Megen in the old meanders of the Meuse. These areas have the highest number of active beaver dens, as well as lower river velocities as they lie outside of the main Meuse channel. Therefore, these locations will be analysed in the following section addressing design wave heights during extreme discharge.

### *5.2.2. Wave analysis*

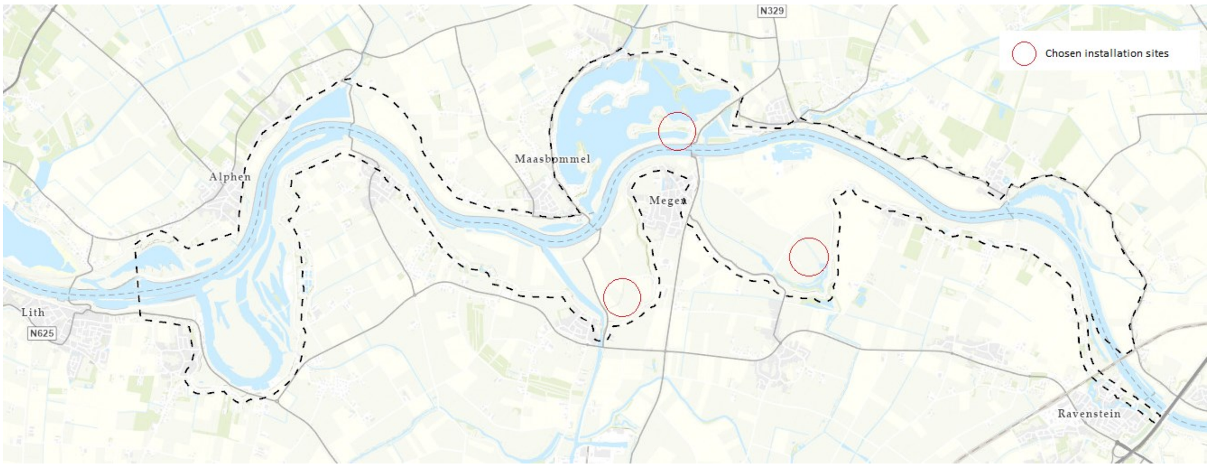
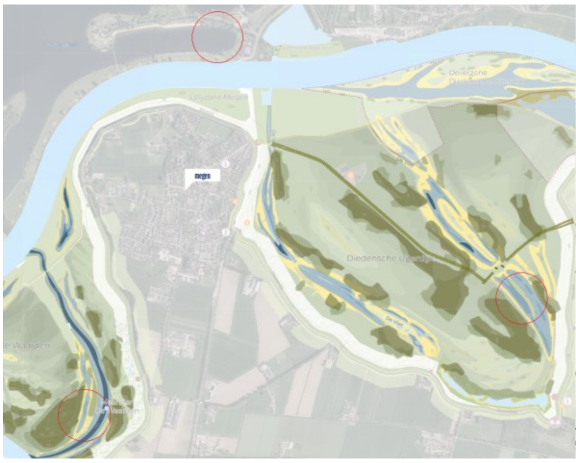



*Figure 24: chosen installation sites*

The map above shows the locations that were selected for further analysis on installation feasibility, and whose selection was conditional on beaver presence and topography. Following from this, the wave heights are addressed in this chapter.



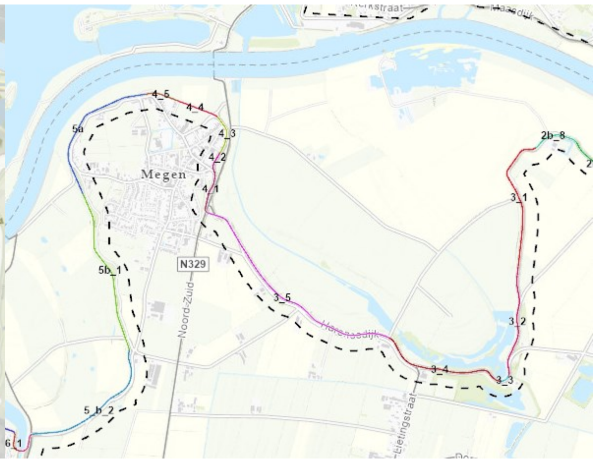



*Figure 25: proposed wetland nature park (Source: meanderendemaas.nl)*

*Figure 26: dyke section groups (Source: aaenmaas.nl)*

The selected areas east and west of Megen fall within the bounds of the proposed nature park of the Meanderende Maas project (Figure 25). The old meanders of the Meuse will be made visible again to create value for nature, water quality and recreation (Meanderende Maas, 2021). The development of these 600 hectares creates a suitable landscape for the beavers during low water periods as there will be suitable aquatic conditions, shrubbery, and (small) forests. To the north, the area will remain as it is. The chosen location is part of a sheltered meander lake with a small inlet from the Maas, near which there is an active beaver territory.

Nevertheless, the beaver territories will most likely be inundated during high-water periods and so it is important to provide an alternative to the dykes that the beavers can use. These locations are therefore put forward as installation sites for the floating high-water refuges. They could be put into use during low and high-water periods.

To address the high-water conditions, Figure 26 shows dyke sections whose design wave heights are used to direct the design of the floating high-water refuges. The Meanderende Maas Planuitwerking (plan elaboration) describes the following maximum wave heights for the dyke sections closest to the chosen locations:

- East (3_2): 0,970 m
- North (4_4): 0,780 m
- West (5b_2): 0,890 m

The water pressure exerted by these waves can be converted into point forces which act at a specific height on the structure, thereby causing a moment about the centre of gravity. To counteract this, the centre of buoyancy exerts a counterforce which culminates in the righting moment. The calculations discussed in Chapter 8.6. Effect of waves prove that the maximum righting moments are greater than the maximum acting moments caused by the waves. This means that the final design will remain stable and upright after experiencing such waves.

Therefore, these locations are proposed as final installation sites.

## 5.3.Stakeholder analysis

This sub-chapter seeks to establish the relationships and interests of various stakeholders in relation to the project. These are persons or entities who have an interest in the outcome of the project. This may take shape in the form of influencing the outcome of the project, being affected by the said outcome, or perceiving to be affected by a decision, activity, or outcome of a project (Project Management Institution , 2017).

A stakeholder analysis is an approach used to generate knowledge about actors – individuals and organisations – so as to understand their behaviour, intentions, inter-relations, and interests; and for assessing the interest and influence they bring to bear on decision-making or implementation processes (Varvasovszky & Brugha, 2000).

This stakeholder analysis is used as a tool in the preparation phase of this project to assess the attitudes of various stakeholders regarding the decisions made.

The primary parties involved are:

- **Waterschappen (water boards):** These institutions are charged with the management of surface water quality and quantity in their respective districts. By definition, this extends to the flood defences in the area. As beavers pose a threat to the stability and safety of these dykes by burrowing, the water boards are naturally the first to address the problem. As so many waterboards are affected by the same issue, they share the knowledge gained to guarantee the protection of flood defence systems.
  The waterboards particularly affected are:
  i. Waterschap Limburg
  ii. Waterschap Aa en Maas
  iii. Waterschap Brabantse Delta
  iv. Waterschap Hollandse Delta
  v. Waterschap Rivierenland
  vi. Waterschap Zuiderzeeland
  vii. Waterschap Vallei en Veluwe
  viii. Waterschap Rijn en Ijssel
  ix. Waterschap Drents Overijsselse Delta
  x. Waterschap Hunze en Aa

- **Zoogdiervereniging (Dutch Mammal Society):** The Zoogdiervereniging is a nature conservation organisation whose objective is to collect information on mammals living in the wild and to advocate for their protection. As such, they have contributed greatly to the efforts of this research by providing pragmatic information on beavers and their behaviour in Dutch waterways. As such, the decisions in this research have been greatly determined by consultation with professionals from this body.

- **STOWA:** STOWA is an organisation that acts as the knowledge centre for the water boards. STOWA develops, collects, disseminates, and implements applied knowledge that water managers need to properly carry out the tasks they face in their work. This knowledge can be in applied technical, natural science, administrative-legal or social science field. When knowledge is lacking for water boards to be able to carry out their work properly, it is the task of STOWA to collect this knowledge or to develop and implement it (or have it developed). As it turns out, there is insufficient knowledge about beaver management at the water boards to guarantee flood protection. Hence, STOWA is responsible for contributing to this development.

- **Rijkswaterstaat:** Rijkswaterstaat is the governmental body tasked with the practical execution of public works and water management, including the construction and maintenance of waterways and roads, as well as flood protection and prevention. Their relation to this project is that they must approve applications for structures placed in national rivers, such as the Meuse (Dutch: Maas), where this research intends to install and monitor the high-water refuges. In addition, they manage a large amount of land in the project area and thus their approval is required to move forward.

- **Vereniging van Natuurmonumenten:** Natuurmonumenten is a conservation organisation that protects and enhances natural areas and cultural heritage sites throughout the Netherlands. They purchase, protect, and manage these reserves as per the policies drawn up by their internal board (Natuurmonumenten, 2018). Their role in this research is that they are a core stakeholder in the Meanderende Maas project. This is a nature restoration and dyke strengthening project conducted between Ravenstein and Lith, in which they are charged with the strengthening of nature in this area and are also a predominant landowner/manager. This is expounded further in the subsequent sub-Chapter 6.2: Location Analysis.

- **Provincie Noord Brabant:** The province is responsible for enforcing the European habitat guidelines, the Wet Natuurbescherming (Nature Conservation Act) and the Natuurnetwerk Nederland (Netherlands Nature Network). For each province, the fauna management unit ensures systematic fauna management (high water refuges included) which must be approved by the province (Dijkstra V. , 2017).

- **Hoogwaterbeschermingsprogramma:** The aim of this collaboration is to ensure that by 2050 at least 1,500 kilometres of dykes and approximately 500 locks and pumping stations will be reinforced in such a way that they meet the safety standards that are a result of the Waterwet (Water Act of the Netherlands). Being so integral to the project, they have an influence on the inclusion of high-water refuges for beavers.

- **Public:** Local users of the development of the Meanderende Maas, such as hikers or birdwatchers, may affect the success seen in the installation of high-water refuges for beavers. This may manifest itself, for example, by vandalism of the structures or disturbance of the beavers by dogs.

The influences of these stakeholders are evaluated via a matrix, which grades the stakeholders by order of power – influence on decisions made in the floating high-water refuge implementation – and by interest – investment in the outcome of the implementation. The placement is based on the following participation levels:

### 5.3.1. Clarification participation level

The different participation levels define to which extent a stakeholder is involved in a project. This is dependent on the stakeholders' interests and power, keeping bottlenecks and wishes in mind. The participation level determines how much and in which way a stakeholder is involved and participates. The participation levels are:

1. Inform:

This is the lowest level of participation, often chosen as a participation strategy for the public. The public is informed about the proposed action. Nothing is expected from the public but taking in the provided information. In doing so, a few factors are important:

a. Reaching as many people/parties as possible. The means of communication is dependent on the target audience. Therefore, a communication strategy is advised.
b. The transparency in communicating. By being transparent resistance can be prevented.

2. Consult:

The stakeholder is consulted about proposed plans. The higher the number of different options presented, the greater the openness to content. This form of participation can be very non-binding; in fact, only the opinion of the stakeholder is considered, and this opinion does not necessarily have consequences.

3. Partnership:

This stakeholder is given room for discussion and allowed to propose their solutions. They are therefore allowed to advise and may have a role in funding the operation. They have more say because their collaboration is more vital to the success of the project.

4. Control:

Some of the decisions are to be made by these stakeholders. A large degree of participation must be requested. It is necessary that the entire process from start to finish is actively followed and transparent to them, and that sufficient knowledge is available to participate in decision-making in a fully-fledged and responsible manner. All parties have an equal position and role in the project.

| Power | Low interest | High interest |
|---|---|---|
| High | **Partnership**<br>Provincie Noord-Brabant<br>Hoogwaterbeschermingsprogramma (HWBP) | **Control**<br>Rijkswaterstaat<br>Natuurmonumenten<br>Waterschap Aa en Maas<br>Waterschap Rivierenland<br>STOWA<br>Zoogdiervereniging |
| Low | **Inform**<br>Public | **Consult**<br>- |

The various interested parties and their points of concern and/or potential conflict are herein identified, along with proposals for managing said points of concern. These are organizations that directly or indirectly affect the outcome of the intended direction of this research, and whose input is therefore required for a result that is in harmony with their wishes.

| STAKEHOLDER | INTERESTS | BOTTLENECKS | SOLUTIONS |
|---|---|---|---|
| **RIJKSWATERSTAAT** | - Unobstructed flow of the Meuse/Maas | - High-water refuge causing obstruction to flow | - Analysis of river flow and sheltered areas |
| **NATUURMONUMENTEN** | - Natural values<br>- Fit into landscape<br>- Habitat and fauna conservation | - Spatial planning (land ownership)<br>- Permit and exemption applications | - Permit and exemption applications<br>- Prioritization<br>- Consultation and feedback |

| | | | |
|---|---|---|---|
| **WATERSCHAP AA EN MAAS** | - Production of high-water refuges (HVPs)<br>- Protection of dyke (flood safety) | - Conflicts with other stakeholders<br>- Use of HVPs by beavers | - Permit and exemption applications<br>- Prioritization<br>- Consultation and feedback |
| **WATERSCHAP RIVIERENLAND** | - Production of high-water refuges (HVPs)<br>- Protection of dyke (flood safety) | - Conflicts with other stakeholders<br>- Use of HVPs by beavers | - Permit and exemption applications<br>- Prioritization<br>- Consultation and feedback |
| **PROVINCIE NOORD BRABANT** | - Economic prosperity from Meanderende Maas project<br>- Tourism<br>- Safety<br>- Low interference with other users of area | - Spatial planning (land ownership)<br>- Permit and exemption applications<br>- Low interference with other users of area | - Permit and exemption applications<br>- Prioritization<br>- Consultation and feedback<br>- Positioning away from high traffic areas |
| **ZOOGDIERVERENIGING** | - Minimisation of beaver-human conflicts | - Ensuring use of refuges by beavers | - Regular consultation<br>- Integration into research, installation, and monitoring phases |
| **HOOGWATERBESCHERM-INGSPROGRAMMA (HWBP)** | - Source of funding for project (Meanderende Maas) | - Pilot needs to be approved for fit into larger project | - Consultation for feedback |
| **STOWA** | - Source of funding for project (HVP) | - Project needs to be approved for funding | - Consultation and feedback to seek approval |
| **PUBLIC** | - Tourism | - Human-animal conflicts | - Positioning away from high traffic areas |

# 6. Concept design

The values in green from the worked-out multi-criteria analysis show the highest scoring alternatives. This gives a combined system made up of the following components and materials:

1. Anchorage: weighted rope
2. Material choice:
   a. Floats: reinforced EPS blocks
   b. Roof: fibre cement sheets
   c. Insulation: polyurethane foam
   d. Platform: recycled plastic boards
   e. Walls: recycled plastic panels
3. Entrance: sheltered

This breakdown shows the composition of the structure but does not bear on the conceptual design of the refuge itself. In order to satisfy the requirements outlined in Chapter 3: List of design requirements, some additional points of concern need to be addressed in the design. The design provisions here need not be analysed by an MCA as they would be implemented regardless of other considerations (no trade-offs).

**1. Dimensions**

The size of the structure should be such that a beaver family can use the structure comfortably. Therefore, the following dimensions are proposed as a minimum, some of which are adjusted by the stability calculations made in Appendix D: Hydrostatic calculations.

i. The main entrance shall be 35 cm*35 cm. This allows for easy entrance and egress from the structure while limiting the amount of airflow through the refuge. This decision is based on an average diameter of 35 cm of a beaver burrow (Verbeylen, et al., 2003).

ii. A rear opening should be provided to allow intruding animals such as otters, other beavers, or birds, to escape without conflict. The dimensions for this are to be 25 cm*25 cm, which provides ample space for these animals to escape. For example, adult [Eurasian] otters can squeeze through a gap of 12 cm (Dijkstra V. , HVP Evaluation Criteria, 2022). The inclusion of this exit hole would cause the development of a draught through the refuge, but it is expected that the beavers would block the hole with twigs and mud when the structure is in use.

iii. The inner dimensions of the structure shall be at minimum 2m*2m. This provides adequate space for a large beaver family of 8, consisting of a mating pair and their 3 consecutive litters of 2 kits each (Dijkstra V. , HVP Analysis Criteria, 2022). However, the average family size is 4.5 animals (Dijkstra V. , Omgaan met de bever, 2020).

iv. As established in consultation with professionals from the Zoogdiervereniging, the inner height of the structure at the lowest point should be 40 cm. This allows the beavers to move without constraint.

v. The structure will be accessed from the water using a ramp of minimum 25 cm width. This ramp should be positioned such that it does not catch on floating debris such as branches or trees.

**2. Roof**

The roof shall be sloped to keep precipitation (rain, hail, snow) from collecting and potentially leaking into the refuge.

**3. Monitoring cameras**

Wildlife cameras shall be installed on the interior and exterior to monitor the actual use of the floating refuge. These should not encroach on the beavers' activities and as such should use infrared LEDs for low-light capture. Moreover, they should be easily accessed for maintenance and repair. A small window or shutter built into one of the walls would facilitate this.

**4. Maintenance door**

The interior of the structure may require periodic maintenance or cleaning. An opening mechanism allowing humans to access the interior should be included in the design.

**5. Points of anchorage**

The entrance and exit of the structure should be positioned at the downstream end of the structure. This minimises the chance that debris gets caught on the ramp/gangway and also reduces the chance of large waves wetting the interior. Moreover, the tension on the anchorage points provides a counter force to the eccentric load of the beavers which is expected to act primarily between the two inner walls, as seen in Chapter 8.2. Centre of gravity.

**6. Iron plate**

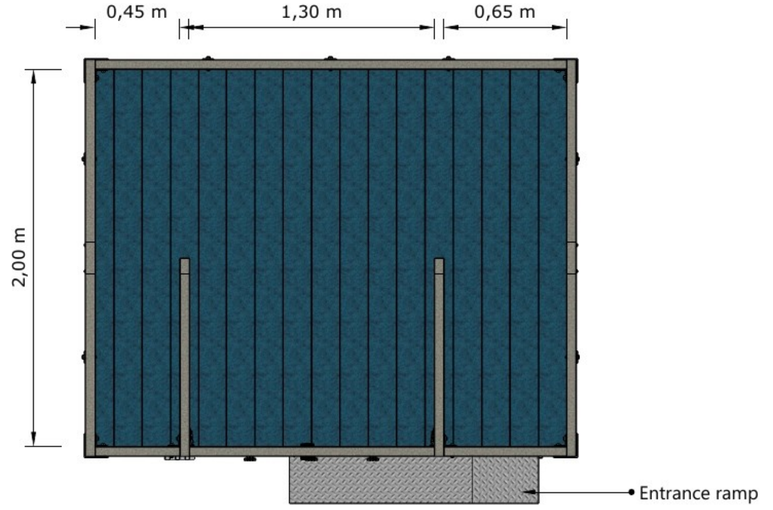
Stemming from preliminary hydrostatic calculations, it was realised that the centre of gravity of the structure was too high, hence causing instability. A solution to this is to use iron plates of 0,5 cm thickness to cover the tops of the floats. This reduces the centre of gravity to a suitable height. Additionally, these spread the load of the refuge across the floats uniformly and therefore reduce the need for maintenance or replacement.

The decisions made above were finalised using the following iterative process:

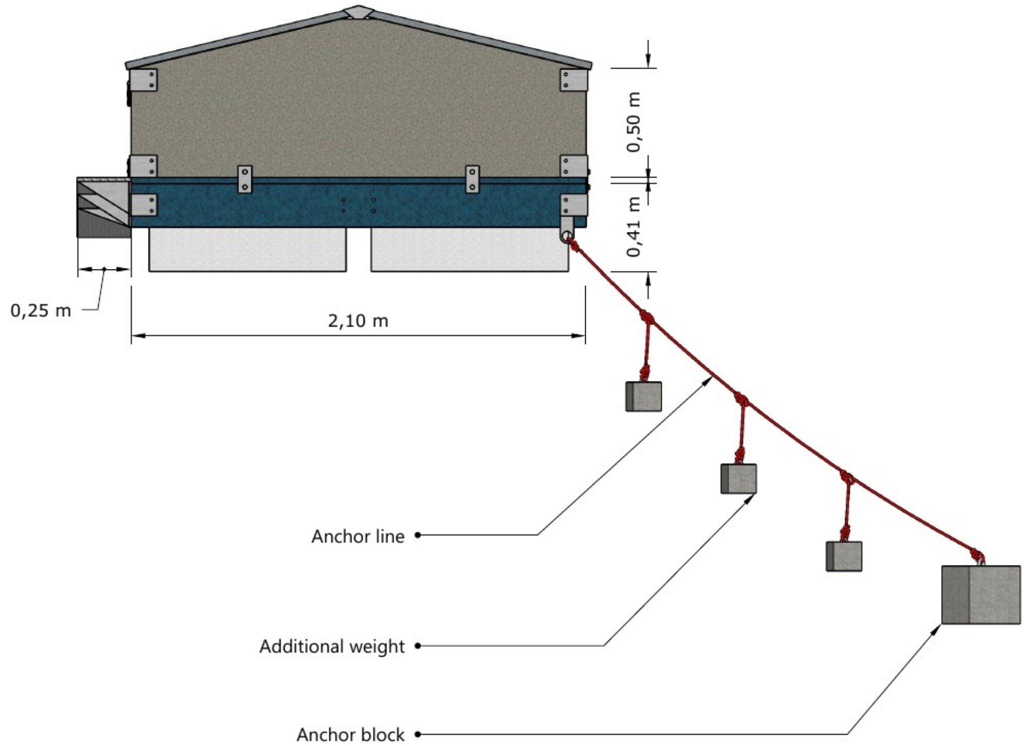
i. Data collection from literature
ii. Interviews/meetings with involved professionals
iii. Drafting list of design requirements
iv. Drafting concept designs
v. Consultation on concept ideas
vi. Reviewing suitable components and materials
vii. Consultation on suitable weights and criteria
viii. Finalising material and component choice via MCA
ix. Stability calculations for each concept
x. Settling on the final choice of materials, components, dimensions

A printout of the final design with all the finalised dimensions and material choices is presented on the following page.

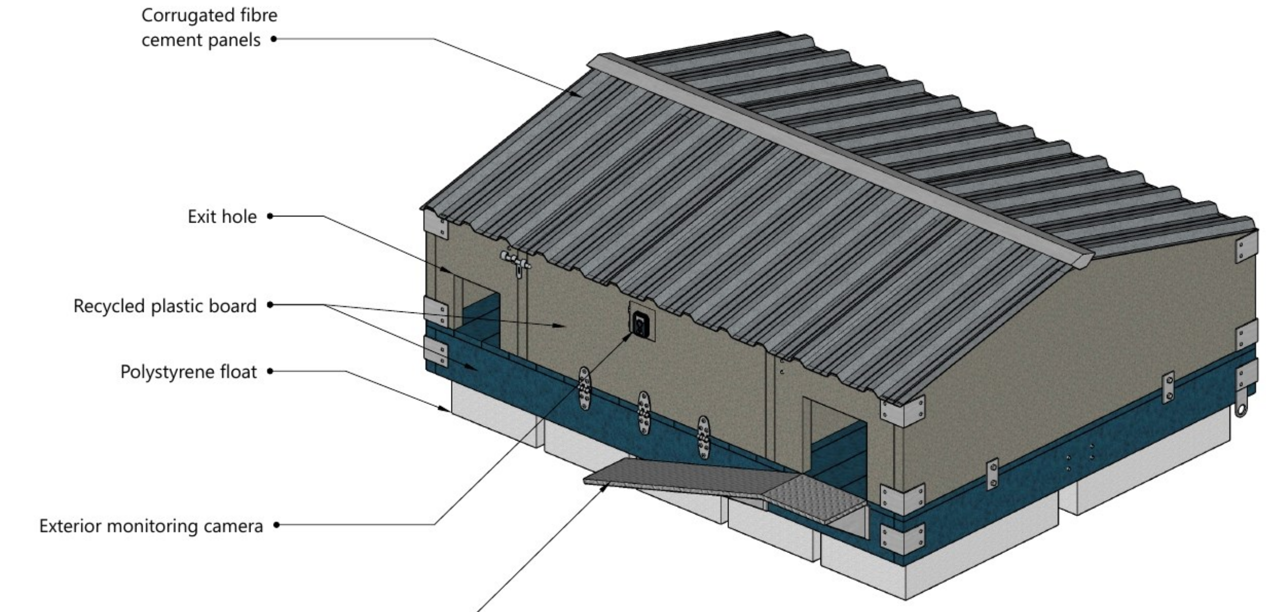
TOP VIEW

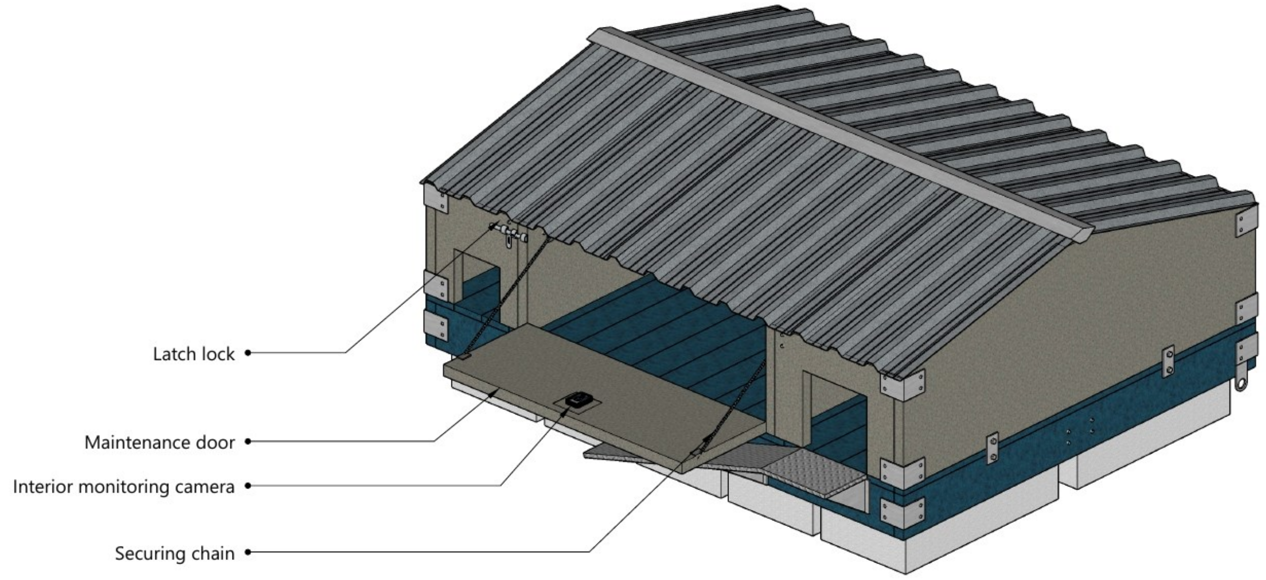



SIDE VIEW - ANCHORS




ISOMETRIC VIEW

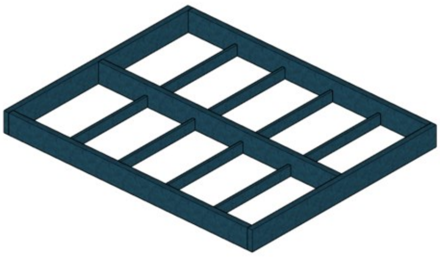


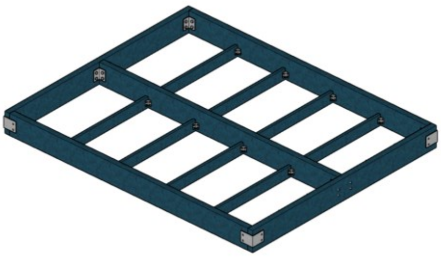

| | |
|---|---|
| **Hoogwatervluchtplaatsen** | Christian Gerrits |
| | 12/06/2022 |
| Final concept | Waterschap Aa en Maas<br>HZ University of Applied Sciences |

# 7. Assembly

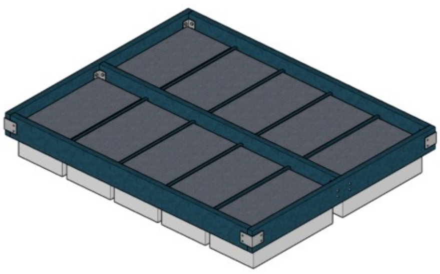
It is common practice when building a floating dock or jetty to transport the material in parts to the location of installation and before then assembling the structure on-site (Dock Edge +, 2021). This method shall be used for the construction of the floating high-water refuge.



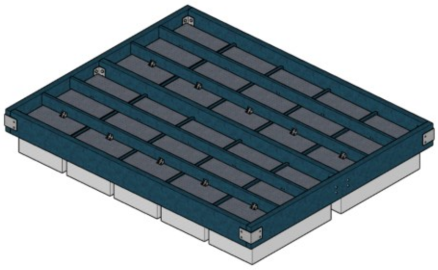
The frame or base is first constructed after ensuring all the boards are of the correct length. The joist headers are the outermost boards and are therefore laid down first, using the equally spaced bottom joists to maintain correct spacing before securing the bolts in place. Lock washers should also be used to keep the bolts and nuts from loosening.



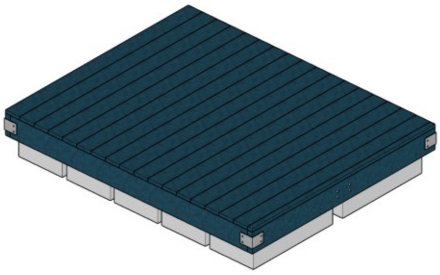
The frame's shape is reinforced by the use of corner plates on the inside and backer plates on the outside. These maintain the rigidity of the frame.



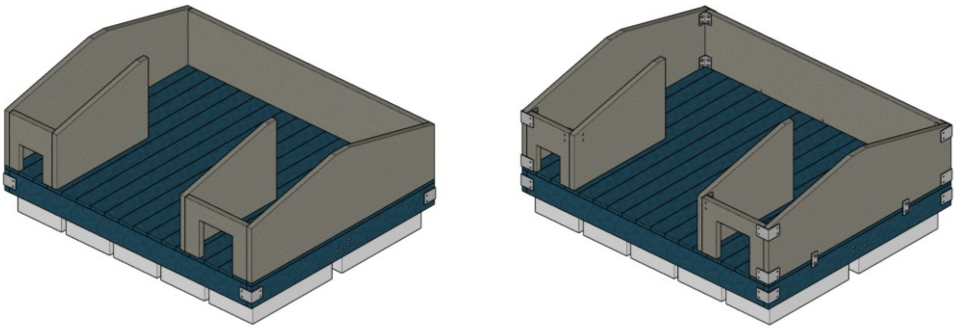
Next, the expanded polystyrene floats will be placed into the equally sized compartments between the bottom joists. Following from this, the entire frame should be lifted and placed on supports to allow the installation of the top joists.



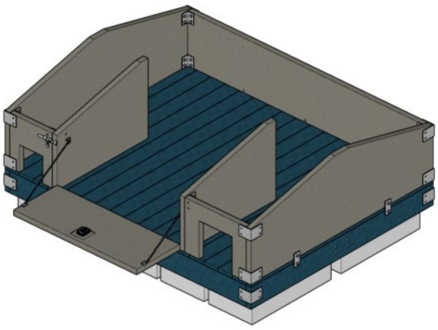
The top joists will then be placed on top of the bottom joists and flush with the top of the joist headers. After fastening them in place, the supports can be removed, and the frame left to rest on the floats. The floats can then be secured to the top joists using bolts screwed through corner plates. Polyurethane foam may then be applied between the gaps to keep water and insects from infiltrating the base platform. Moreover, they minimise draught development through the floorboards to retain heat.

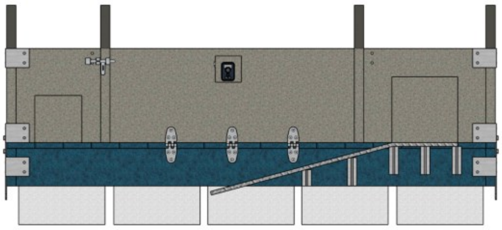


Finally, to complete the construction of the platform, the deck boards will be screwed to the outer joist headers and to the inner top joists. The screw holes should be marked or drilled beforehand to ensure accuracy.

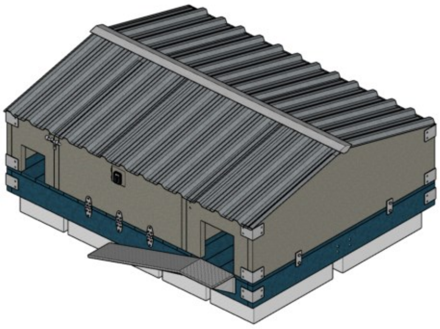


The walls of the superstructure can then be erected and secured in place using the same corner and backer plates as were used for the base platform. The connection between the platform and the walls will be facilitated by overlapping fishplates, two on each of the shorter sides and three on the longer back panel.

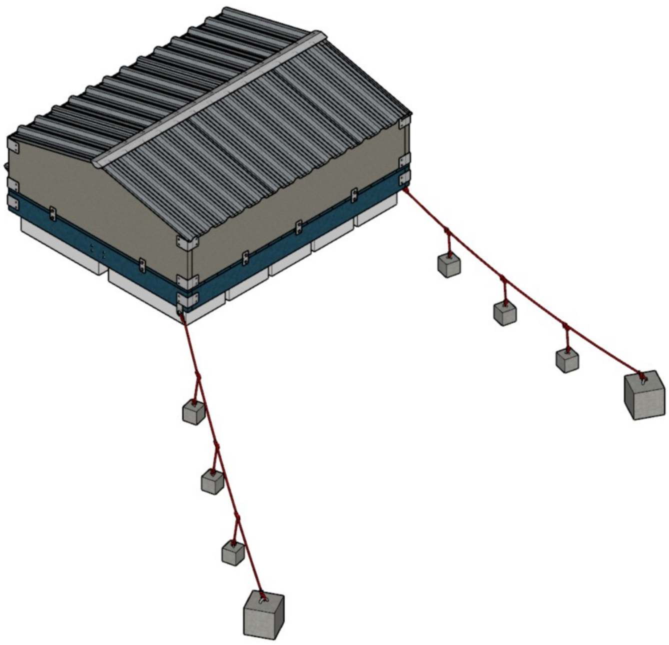




The maintenance wall may then be installed. The hinges and chains are first secured before fastening the panel to these points. The chains limit the rotation of the wall outwards in order to keep the hinges intact. A sliding latch lock is used to hold the wall in place. A point of attention is that the monitoring camera window may be installed prior to this step.



The next step would be to install the access ramp/gangway and the roof. The ramp is braced by triangular support brackets connected to the joist header. The roof sections may be simply nailed to the walls before attaching the ridge cap on the top, which prevents leaking.



At this point, the structure may be put on the water and floated into position before securing the weighted ropes to the back of the structure such that the openings point downstream.

# 8. Results and discussion

The static stability of a floating structure encompasses the righting properties of the structure when it is brought out of its state of equilibrium by a disturbance such as waves or wind. As a result of these loads, the structure will translate linearly and/or rotate about its centre of gravity.

The static and dynamic properties of the structure play a role in this. The dynamic effects of the live loads (beavers) presented in this chapter are ignored because it is assumed that the changes to the state of equilibrium will be brought about slowly enough that all dynamic effects can be ignored. The effect of the waves is also analysed statically by determining the righting arm required to overcome the moment they induce. It is a recommendation of this research to delve deeper into the dynamic analysis by investigating the wave orientation and frequency or period. For now, it should suffice to prove that the structure can overcome the rotation induced.

In this chapter, the conclusive goal is to determine the stability of the floating high-water refuge when it is presented with the vertical load of the beavers and horizontal load of waves. For this, the formulae presented in the theoretical background (Hydrostatic principles) will be used to determine whether the choice of dimensions and material are adequate to attain statical stability. The worked equations may be found in Appendix D: Stability calculations.

*A link to the relevant tables is provided at the end of each section*.

## 8.1. Mass

The mass of the structure is the first to be determined as it is the most important parameter. This is because it influences all subsequent calculations.

Here, the structure was divided into the different components and elements, whose dimensions, unit weights and quantity were multiplied to derive the mass per component. Furthermore, the masses are grouped into floats, refuge (superstructure), and beavers as this is relevant for later calculations. This gave the following results:

| **Component** | Floats | Platform | Walls | Roof | Ramp | Beavers |
|---|---|---|---|---|---|---|
| **Mass** | 375,98 | 191,60 | 179,88 | 77,89 | 10,00 | 130,00 |
| | | 459, 378 | | | | |
| **Total mass** | 965,36 | | | | | |

It is evident that the floats and platform provide the bulk of the mass, which is favourable because they are the lowest lying components. This acts to reduce the height of the centre of gravity, making the structure more stable. It seems counter-intuitive that the floats provide the largest mass and yet are responsible for keeping the structure buoyant. However, this is because they also have the lowest composite unit mass and hence the largest volume. Moreover, the relatively high mass of the structure increases the inertia against wave impact. The entirety of the calculations can be found in Appendix D.I: Mass.

The various physical material properties used may be accessed via the following databases:

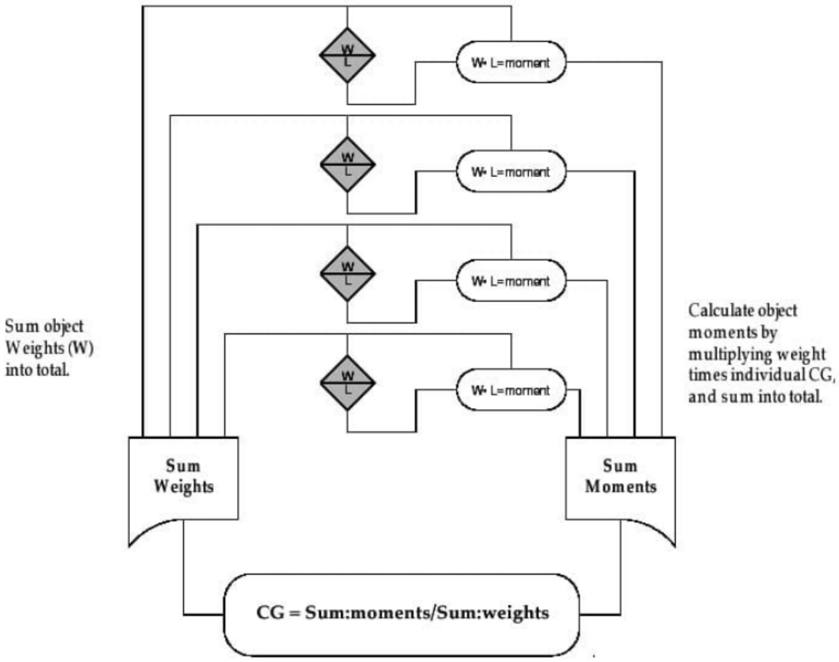
https://www.matweb.com/search/PropertySearch.aspx
https://www.reworked.com/tech-specs/

## 8.2. Centre of gravity

The centre of gravity is the next step in the calculations. This value will be useful in determining the metacentric height in coordination with the centre of buoyancy.

This is determined by first determining the midpoints of each element (done using the SketchUp model), which are then multiplied by their respective weights to determine their moments relative to the datum for a specific axis.

After that is completed, the sum of the moments is divided by the sum of weights. This results in a moment arm which presents the centreline of the structure's mass relative to this axis. Hence, to determine the centre of gravity of the structure, this process must be repeated for each axis.

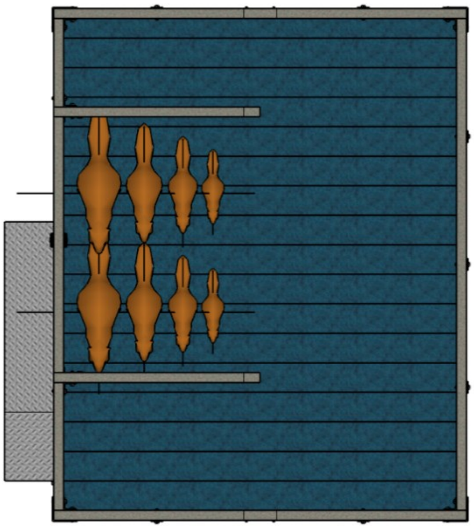
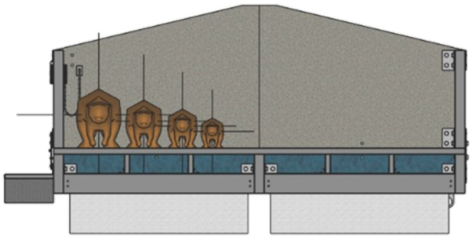



To facilitate the metacentric height calculations, the centres of gravity are determined on a case-by-case basis, in addition to the composite centre of gravity. The different cases are as follows:

i. Floats alone
ii. Floats + refuge load
iii. Floats + refuge load + beaver load

A point of clarification is that "refuge" here refers to the superstructure, composed of the platform, walls, roof and ramp. Moreover, the beaver load is considered to be a quasi-permanent part of the structure and is hence factored into the last case. The same does not go for waves as they provide an external temporary load.

The figures below show the normative layout assumed for the calculations in Appendix D: Centre of gravity. The distribution of the beavers is based on the assumption that the animals would collect in the space between the inner walls as it is likely to be warmer here. More importantly, this provides the greatest moment about the x-axis (shorter direction) that should be accommodated by the structure.

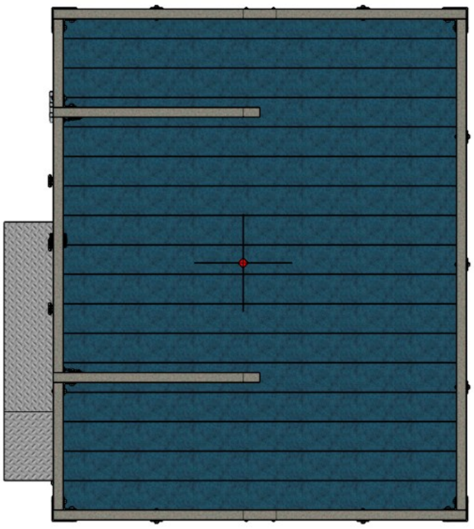
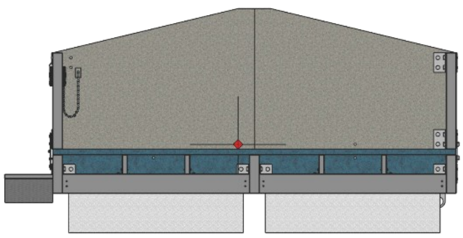
A summary of the calculation results:

| Z: AXIS | Floats | Refuge | Beavers |
|---|---|---|---|
| **Per component** | 0,219 | 0,623 | 0,576 |
| **Floats + refuge load** | 0,441 | | |
| **Floats + refuge load + beaver load** | *0,459* | | |

| Y: AXIS | Floats | Refuge | Beavers |
|---|---|---|---|
| **Per component** | 1,300 | 1,300 | 1,241 |
| **Floats + refuge load** | 1,300 | | |
| **Floats + refuge load + beaver load** | *1,292* | | |

| X: AXIS | Floats | Refuge | Beavers |
|---|---|---|---|
| **Per component** | 1,050 | 1,042 | 0,444 |
| **Floats + refuge load** | 1,046 | | |
| **Floats + refuge load + beaver load** | *0,965* | | |

The composite centre of gravity (floats with refuge and beaver loads) is graphically represented below by the red point. It can be seen that the centre of gravity shifts in the direction of the beavers. The entirety of the calculations can be found in Appendix D.II: Centre of Gravity.

## 8.3. Buoyancy

The purpose of this research is to develop a floating structure, so it stands to reason that buoyancy should be guaranteed.

The principles outlined in Chapter 2.8.1. Archimedes' law state that the force of buoyancy is equal to the weight of a floating structure. A buoyant object sinks in a fluid until an equal weight of the fluid is displaced, at which point it floats. Therefore, the composite density of the body has to be less than the density of water if it is to keep afloat. The lower the density, the higher the object floats, whereas the higher the density, the further it sinks.

$$F_A = \rho_f g V$$

Consequently, the maximum buoyant force is experienced when the structure is fully submerged and has displaced the maximum volume of fluid. For this calculation, it will be assumed that buoyancy is only provided by the polystyrene floats but in reality, this will be more favourable.

The buoyant forces experienced by the floats alone, by the floats and all dead loads, and finally by the floats when they are fully submerged, are summarised by the following table.

| | |
|---|---|
| **Buoyant force (no load; N)** | 3688,41 |
| **Buoyant force (full load; N)** | 9470,21 |
| **Max buoyancy (floats submerged; N)** | 12730,04 |

The maximum buoyancy exceeds the worst-case scenario (full load) by more than 30%. The floats are therefore more than sufficient to bear the weight of the refuge and its residents.

The centres of buoyancy must also be calculated to determine the tilt of the structure at rest (zero wave conditions). This is done because the structure's loads are evidently not symmetric across the floats.

The centre of buoyancy of the floats (zero load applied) will first be calculated using the same formula as used for the centres of gravity. The shifts in the centre of buoyancy after loading will then be calculated using the formulae below from Chapter 2.8.4. Tilt. The horizontal calculations are done twice, once for each horizontal direction (x and y axes).

$$B_0B_{1;\,horizontal} = \frac{a * m}{\rho . V_0 + m}$$

$$B_0B_{1;\,vertical} = \frac{\left(BO + \left(\frac{d}{2}\right)\right) * m}{\rho . V_0 + m}$$

Moreover, the contact area, draft, and freeboard are calculated per case as the results are used in the centre of buoyancy calculations. The results are summarised on the subsequent page.

i. Floats:

| Mass (kg) | Volume (m³) | Contact area (m²) | Draft (m) | Freeboard (m) |
|---|---|---|---|---|
| 375,985 | 0,376 | 4,186 | 0,090 | 0,345 |

| | Weight (N) | Moment (Nm) | CB (m) |
|---|---|---|---|
| **Z axis** | 3688,412 | 165,646 | *0,045* |
| **Y axis** | 3688,412 | 4795,009 | *1,300* |
| **X axis** | 3688,412 | 3872,833 | *1,050* |

This centre of buoyancy, denoted CB, shall be used as the initial value ($B_0$) from which the shifts below are calculated. The volume ($V_0$) is similarly used.

ii. Refuge load:

| Mass (kg) | Volume (m³) | Contact area (m²) | Draft (m) | Freeboard (m) |
|---|---|---|---|---|
| 835,363 | 0,835 | 4,186 | 0,1996 | 0,235 |

The shift in the centre of buoyancy is summarised by the following results.

| | Y axis | X axis |
|---|---|---|
| **Horizontal ($B_H$)** | 0,000 | 0,004 |
| **Vertical ($B_V$)** | 0,030 | |

Deducting and adding these values to the initial CB gives the following results:

| | CB (m) |
|---|---|
| **Z axis** | *0,075* |
| **Y axis** | *1,300* |
| **X axis** | *1,046* |

iii. Refuge load + beaver load:

| Mass (kg) | Volume (m³) | Contact area (m²) | Draft (m) | Freeboard (m) |
|---|---|---|---|---|
| 965,363 | 0,965 | 4,186 | 0,2306 | 0,204 |

| | Y axis | X axis |
|---|---|---|
| **Horizontal ($B_H$)** | 0,008 | 0,085 |
| **Vertical ($B_V$)** | 0,043 | |

| | CB (m) |
|---|---|
| **Z axis** | *0,088* |
| **Y axis** | *1,292* |
| **X axis** | *0,965* |

The bulk of the calculations may be accessed in Appendix D.III: Buoyancy.

## 8.4. Metacentric height

The distance between the metacentre and the centre of gravity is an indicator of stability in that the metacentre is the point about which the structure heels. The higher this point, the greater the stability whereas the lower it is, the lower the stability.

Similar to the previous calculations, this section was done per loading case to observe the effect on the stability. The formulae used are found in Chapter 2.8.5. Metacentre. The results are summarised as follows:

| | | MG |
|---|---|---|
| **FLOATS** | Y-axis | 4,734 |
| | X-axis | 2,899 |
| **REFUGE LOAD** | Y-axis | 1,868 |
| | X-axis | 1,042 |
| **REFUGE + BEAVER LOAD** | Y-axis | 1,568 |
| | X-axis | 0,853 |

The results are positive for every loading case and axis, therefore proving that the structure is statically stable.

This means that if an external rotation is imposed on the structure, it will return to its original resting point, which resting point is expounded below under the subchapter addressing tilt. The extent to which it may be rotated before capsizing is further elaborated in 8.6. Effect of waves.

## 8.5. Tilt

Here, the position of the structure relative to a calm waterline is addressed. The reason for this is that the buoyant forces and the centres of gravity act on different lines through the structure, forcing the structure to bank in one direction. This submerges one side to a greater extent than the opposite side. It must be ensured that the deck remains above the water level even after loading.

The formulae used are found in Chapter 2.8.4 Tilt while the results are presented more in-depth in Appendix D.V: Tilt.

REFUGE LOAD

| | Y axis | X axis |
|---|---|---|
| G0G1 | 0,0001 | 0,0044 |
| MG0 | 1,8676 | 1,0418 |
| z | 0,0001 | 0,0041 |

REFUGE + BEAVER LOAD

| | Y axis | X axis |
|---|---|---|
| G0G1 | 0,0081 | 0,0854 |
| MG0 | 1,5675 | 0,8529 |
| z | 0,0050 | 0,1042 |

The last value, z, presents the difference in height between the initial and final positions of the structure's extremities. The highest value of 10,42 cm is the result of a 5,7 ° rotation about the metacentre. The significance of this is that the deck remains dry even after the rotation.

## 8.6. Effect of waves

Here, the rotation induced by the waves encountering the side of the structure is analysed.

The waves are reduced to a single force acting at a point one-third of the wave height from the keel or bottom of the structure. This produced a turning couple about the centre of gravity, which is in turn countered by the righting moment. This counter moment is produced by the buoyant force acting in tandem with the righting arm/lever. This righting arm is denoted GZ.

The maximum expected wave heights per location are outlined in Chapter 5.2.2. Wave analysis. The forces generated are calculated using the following formula from the theoretical background:

$$F_{max} = \frac{1}{2}\rho g H_i^2 + d\rho g H_i$$

This results in the following acting moments:

| | 3_2 | 4_4 | 5b_2 |
|---|---|---|---|
| **$H_i$ (m)** | 0,970 | 0,780 | 0,890 |
| **Fmax (N)** | 4388,97 | 3529,27 | 4026,99 |
| **Arm (m)** | 0,400 | 0,337 | 0,373 |
| **Moment (Nm)** | 1756,49 | 1188,91 | 1504,24 |

The righting arm required to neutralise the rotation is calculated by working backwards from the determined acting moments. The force in the righting moment is provided by the buoyancy of the structure, which is equal to the mass at full load (refuge load + beaver load).

| | 3_1 | 4_4 | 5b_2 |
|---|---|---|---|
| **Moment (Nm)** | 1756,489 | 1188,914 | 1504,238 |
| **Buoyancy (N)** | 9470,21 | 9470,21 | 9470,21 |
| **$GZ_{min}$ (m)** | 0,1855 | 0,1255 | 0,1588 |

As is evident from the table above, the minimum righting arm values fall between 12,55-18,55 cm. It must consequently be proven that the structure can provide (at minimum) such righting arms in to overcome the wave-induced rotations and bring the structure back upright.

The maximum righting arm can be determined using a GZ curve, whereby the righting arm values are plotted against the respective heeling angles for a specific floating structure.

In order to produce such a curve, the hull design software PolyCAD 10.5 was used. This required the use of shape files which were then analysed for geometry and accordingly mapped in PolyCAD. The floats and deck were used as a proxy for the whole structure in order to maintain a more favourable result in reality. It must be stated that the mass and consequent displaced volume remain the same for the stand-in as for the whole floating refuge.

For the righting moment to overcome the induced rotation, the rotation must remain within the limits of the heel angles described by the bespoke GZ curve below. The floating refuge will remain stable if the rotation causes a positive GZ : heel angle ratio. That is to say, the point of intersection should remain in the first and third quadrants (top-right and bottom-left) for the structure to right itself, regardless of whether the deck has been submerged. Outside of this, the structure will capsize.

This video provides an animated explanation.

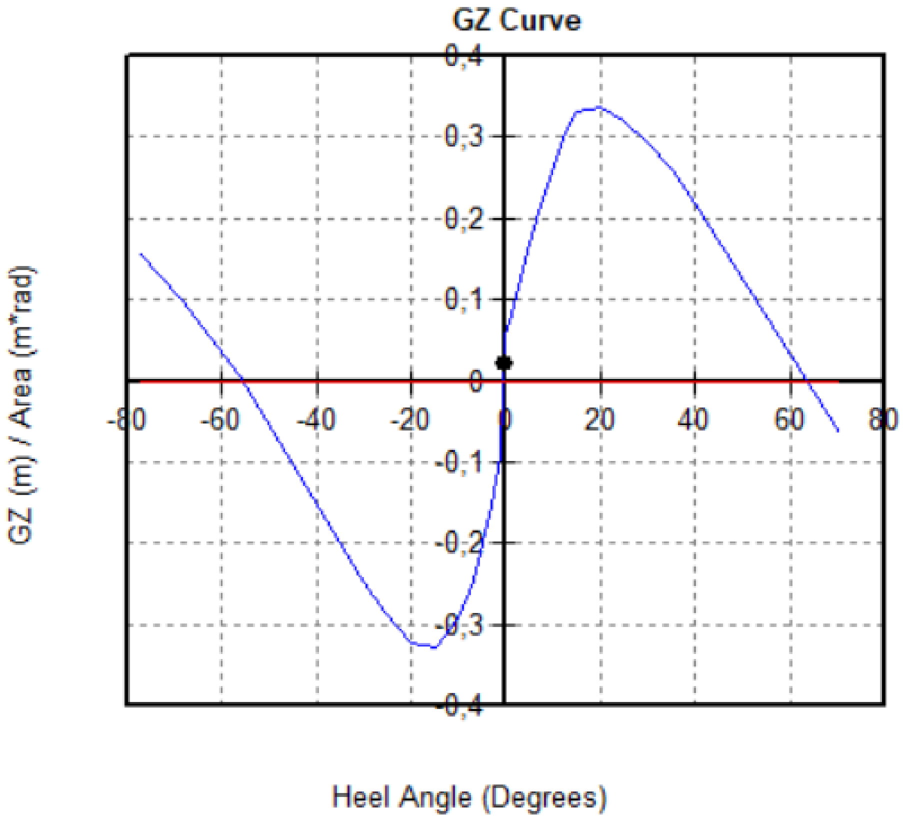



*Figure 27: relationship between righting arm and heel angle for finalised floating HVP design (Source: PolyCAD analysis)*

The maximum heel angle extends to 63 ° on the front side of the structure (side with openings) and to 56 ° on the back side. The maximum righting levers are also evident as 33,8 cm for the front side and 32,8 cm for the back side. These values far exceed the minimum required values presented on the previous page 12,55-18,55 cm.

This means that the maximum righting moment is greater than the maximum wave-induced acting moment. The structure will remain upright even in extreme situations.

# 9. Conclusions and recommendations

## 9.1. Research questions

This chapter provides a summary of the key findings of the research along with suggestions on how best to build on or enrich the knowledge gained.

Firstly, the culminating answers to the research questions are presented. The sub-questions are seen to before working up to the primary question.

**1. What is the most optimal choice of materials and components?**

This question sought to determine the most suitable parts of the final structure. An MCA was used to assess the behaviour of various components and materials in relation to desired properties. This resulted in the following choice of materials and components:

1. Anchorage:
   The main driver for the selection of weighted ropes was their simplicity, cost, durability, and resilience against floating debris. These are all properties that aid to fulfil the technical requirements. The stability offered is lower than the other options, but the importance of this factor is lowered by the proven stability offered by the refuge as a freely floating body. The weighted rope should only add to this stability as it acts as a counterforce to the eccentric load of the beavers, keeping the refuge level even when battered by waves. A point of further development would be to dynamically analyse the effect this has on the stability of the structure, provided the wave periods or frequencies at high-water.
2. Material choice:
   a. Floats:
      The reinforced EPS blocks chosen to keep the structure buoyant have the advantages of durability and cost over the other float alternatives. Even if punctured by floating debris, these blocks will remain buoyant due to the sheer number of air pockets.
   b. Roof:
      Corrugated fibre cement roofing sheets were used in the designs owing primarily to their durability. They are less prone to warping, rusting and mould as compared to the other options. Moreover, they absorb the sound of falling rain better than metal-based alternatives.
   c. Insulation:
      Polyurethane foam was chosen to minimise heat loss as well as to keep water and insects from infiltrating the platform. This decision was made owing to its lessened environmental impact over its lifecycle as it can thereafter be easily recycled or burned to harvest some energy back.
   d. Platform + walls:
      Robust boards made from recycled plastic shall be used to construct the primary components of the floating refuge as they are more durable than their wooden counterparts. Manufactured using waste materials, it also has an added benefit to the environment.

3. Entrance:
   It was decided to have inner walls by the entrance and exit to reduce the exposure of the beavers to cold draughts. The space between these corridors may be used as a nesting chamber by the beavers.

**2. Where should the structure be built?**

Eventually, three locations surrounding the "promontory" city of Megen were finalised as these presented the most optimal conditions. By overlapping maps showing different data sets, the following installation sites are proposed, one each to the southwest, north and east of Megen. These evaluations were made in Chapter 5.2. Location analysis.

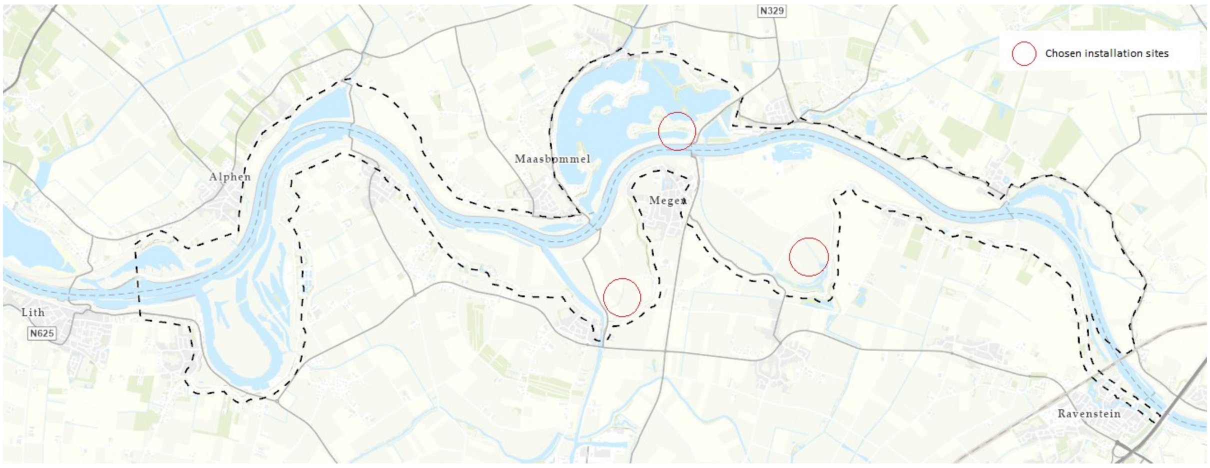



*Figure 28: proposed installation sites*

The choice of these final sites was ultimately dependent on the influence of high-water wave conditions as well as the locations of active beaver territories. However, it will be necessary to further contact the landholders managing these areas, Rijkswaterstaat and Natuurmonumenten, for development on the knowledge of permits and/or exemptions required for the actual installation of the floating high-water refuges.

**3. Will the structure withstand the expected loads?**

To answer this question, the loads experienced by the polystyrene floats were divided into three cases: floats alone; floats and refuge load; and finally, the floats, refuge, and beaver load. The effects on the structure stemming from these changes were then investigated. These effects were manifested in the form of shifts in the buoyant force, the centre of gravity, the centre of buoyancy, metacentric height and finally on the resulting rotations. These loads were then proven to be within the range of values that allow equilibrium. The final design has a maximum buoyant force (25??) 34% greater than the maximum expected load.

After the stability of the structure was proven in zero-flow conditions, the design wave heights of the dykes closest to the installation sites were evaluated. This involved finding the forces exerted on the structure and the resultant acting moment. This imposed rotation then caused a change in the righting arm of the buoyant force. The minimum value of this righting arm was then determined by dividing the acting moment by the buoyant force or weight of the loaded structure. An analysis made through PolyCAD then proved that the maximum righting arm values were over 75% greater than the minimum required to bring the structure back upright in extreme wave conditions.

Finally, to conclusively answer the primary research question:

*What refuge design is the most viable?*

The answer to this question combines elements from the first and third sub-questions as well as the design concept ideas from Chapter 6. Overall, every one of the technical and functional requirements outlined in Chapter 3 was fully addressed by the design provisions outlined in Chapter 6 in tandem with the materials finalised by the MCA in Chapter 5.1. Finally, the dimensions of the final design were determined by the stability calculations made in Appendix D, the relevance of which was discussed in the foregoing Chapter 8.

To summarise, the final design is primarily made of recycled plastic, with polystyrene floats and a cement fibre roof. It is anchored by two weighted ropes that provide tension on the back of the structure and hence greater stability. Moreover, the total dimensions of the floating refuge are a floor area of 2 m*2,5 m with a roof height ranging between 0,5-0,75 m. It is recommended to use the structure in the locations investigated by this research, which would be the 3 areas west, north, and east of Megen described in Chapter 5.2. However, the stability offered by the structure is such that it should withstand greater wave heights than those experienced at the proposed installation sites during high-water periods.

## 9.2. Final remarks

This paper presents experiences with designing and developing a floating high-water refuge, from the introductory stages of literature review and site planning to iterative design and static stability calculations. The idea to experiment with such pilot structures theoretically promises technical success but the de facto adoption by beavers and consequent dyke protection can only be proven by real-world tests. It is the first structure of its kind to be developed for this purpose and hence predictions on paper do not amount to much beyond promising structural integrity and stability.

A point of recommendation for further technical analysis of the design would be to evaluate the wave directions and frequencies at the chosen locations using purpose-built software to produce a more conclusive description of the structure's dynamic behaviour. It is expected that the magnitude and frequency of deck motion correspond to the use of the structure by beavers.

An additional remark would be to continuously monitor the use of the structure after installation in order to determine points of optimisation, be it elements and dimensions of the structure, or its installation location. The adoption of the structure by beavers should be particularly monitored during periods of high-water as the purpose of the floating high-water refuges is ultimately to protect the surrounding dykes after the submersion of beaver dens and lodges.

Finally, this research was made possible largely through the guidance of Ronald Wolters, the technical supervision of Dr Vana Tsimopoulou, and the zoological insight by Vilmar Dijkstra. My deepest gratitude goes out to each of these individuals.

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# Appendices

## A. Broader project approach

- The larger project into which this research fits is supervised by a broad project group, which includes a core group for direct management. Chairman, possibly secretary and participants have yet to be appointed.
- Knowledge of the beavers will be contributed by the Zoogdiervereniging.
- A number of suitable pilot locations are to be determined by participating water managers.
- On the basis of knowledge already acquired in the Netherlands and abroad, a number of possible solutions are being worked out.
- Some water managers, with the cooperation of Rijkswaterstaat and any site managers, are constructing fixed and floating high-water refuges in 'risky' situations. In order to get a reasonable picture of preferences and circumstances in which the HVPs to be installed work well for beavers, it is desirable that several refuge places are constructed per water board.
- All steps, procedures, costs, practical findings (soil type, planting, dimensions), etc. that are necessary for the construction are recorded.
- Development and use of the HVPs are monitored. This will mainly take place during a period of high water. It is impossible to predict the moment that a high water will occur, and this can sometimes take several years. From the moment a high water (from a predetermined level or flow) is announced, targeted monitoring will have to be carried out.
- During high water, intensive monitoring takes place of the behaviour of present beavers and the use of the HVPs (and other animals). For this it is necessary to have an idea of the number of beaver territories in a floodplain. If there are several territories in a floodplain and an HVP is only installed for 1 family, there is still a great risk during high water. How the monitoring will be organized and carried out will be further elaborated in the development phase.
- Knowledge gained is shared with other water managers through the recently established 'Kenniscentrum Bever'.

## B. Overall project schedule

| | |
|---|---|
| **May-June 2021** | search for participants and set up a provisional core group |
| **July-Aug 2021** | summer vacation |
| **Sept-Oct 2021** | search for financing and organizational embedding, further organizing the staffing of the core group and broad project group |
| **Nov-Dec 2021** | further elaboration of the design HVPs |
| **Jan-June 2022** | development floating HVP |
| **Jan-Feb 2022** | identifying mooring locations |
| **Mar-May 2022** | preparations for construction implementation |
| **Jun-Sept 2022** | construction of 1st installment of HVPs |
| **Autumn 2022** | sharing 1st construction findings |
| **2023** | construction of 2nd installation of HVPs |
| **Next high water** | monitoring |
| **Following on from high-water** | evaluating and sharing findings using HVPs |
| **Subject to occurrence of high-water, otherwise move back in time: Spring 2024** | Drawing up best-practice HVPs (reporting) |
| **Annually, from summer 2024*** | Decisions to continue or complete research |

*The planning is very dependent on the construction of the number of HVPs and the occurrence of high waters. If they do not or hardly occur for a few years, experience is unable to be gained. It has therefore been proposed in the planning that from the summer of 2024 it will be decided annually whether the project will be completed or continued.

## C. Personal schedule

| | | |
|---|---|---|
| **Week 1** | 07/Feb | Preparatory week |
| **Week 2** | 14/Feb | Onboarding week at Waterschap Aa en Maas<br>Desk research |
| **Week 3** | 21/Feb | Meetings with relevant contacts<br>Writing up research proposal |
| **Week 4** | 28/Feb | Desk research<br>Writing up research proposal |
| **Week 5** | 07/Mar | In-company meeting with 1st examiner<br>Submission of research proposal for feedback |
| **Week 6** | 14/Mar | Drafting preliminary HVP designs<br>Designing A4 poster<br>Acting on research proposal feedback |
| **Week 7** | 21/Mar | Drafting preliminary HVP designs<br>Meeting with HVP research group<br>Field excursion |
| **Week 8** | 28/Mar | Acting on feedback of designs |
| **Week 9** | 04/Apr | Working on draft version of thesis |
| **Week 10** | 11/Apr | Mid-term day presentation<br>Design production |
| **Week 11** | 18/Apr | Working on draft version of thesis<br>Design production<br>Progress meetings |
| **Week 12** | 25/Apr | Stakeholder meeting<br>Working on draft version of thesis |
| **Week 13** | 02/May | Working on draft version of thesis |
| **Week 14** | 09/May | Working on draft version of thesis |
| **Week 15** | 16/May | Submission of draft thesis + portfolio |
| **Week 16** | 23/May | Optimisation of HVP designs |
| **Week 17** | 30/May | Go/No-go feedback on draft thesis + portfolio |
| **Week 18** | 06/Jun | Acting on go/no-go feedback |
| **Week 19** | 13/Jun | Upload final thesis version + portfolio + overview of study credits |
| **Week 20** | 20/Jun | Final working week<br>Work on presentation defence and complete all necessary documents |
| **Week 21** | 27/Jun | Practice for defence and interview<br>Upload assessment forms<br>Go/No-go presentation |
| **Week 22** | 04/Jul | Upload and present defence |
| **Week 23** | 11/Jul | Permission HBO Kennisbank |

# D. Stability calculations

## *I. Mass*

| Component | Element | Dimensions (m) | | | Volume/area ($m^3/m^2$) | Unit mass ($kg/m^3$ or kg/unit) | Quantity | Element mass (kg) | Component mass (kg) | Total mass (kg) |
|---|---|---|---|---|---|---|---|---|---|---|
| | | L | W | H (average) | | | | | | |
| **Floats** | EPS core | 0,900 | 0,450 | 0,300 | 0,122 | 28,000 | 10 | 34,020 | 375,985 | 965,363 |
| | Cement mortar cover | 0,005 | | | 0,008 | 2162,000 | 10 | 178,711 | | |
| | Iron plate | 0,910 | 0,460 | 0,005 | 0,002 | 7800,000 | 10 | 163,254 | | |
| | Fibre glass | - | - | - | - | - | - | - | | |
| **Platform** | Top joist | 2,500 | 0,025 | 0,100 | 0,006 | 589,000 | 4 | 14,725 | 191,602 | |
| | Bottom joist | 0,975 | 0,025 | 0,100 | 0,002 | 589,000 | 8 | 11,486 | | |
| | Deck board | 2,100 | 0,150 | 0,030 | 0,009 | 589,000 | 17,3 | 96,478 | | |
| | Joist header 1 | 2,500 | 0,050 | 0,200 | 0,025 | 589,000 | 3 | 44,175 | | |
| | Joist header 2 | 2,100 | 0,050 | 0,200 | 0,021 | 589,000 | 2 | 24,738 | | |
| **Walls** | Back | 2,500 | 0,050 | 0,500 | 0,063 | 589,000 | 1 | 36,813 | 179,881 | |
| | Front | 2,400 | 0,050 | 0,500 | 0,060 | 589,000 | 1 | 35,340 | | |
| | Inner 1 | 1,050 | 0,050 | 0,610 | 0,032 | 589,000 | 1 | 18,863 | | |
| | Inner 2 | 1,050 | 0,050 | 0,610 | 0,032 | 589,000 | 1 | 18,863 | | |
| | Left | 2,100 | 0,050 | 0,610 | 0,064 | 589,000 | 1 | 37,725 | | |
| | Right | 2,100 | 0,050 | 0,610 | 0,064 | 589,000 | 1 | 37,725 | | |
| | Entrance | 0,350 | 0,050 | 0,350 | -0,006 | 589,000 | 1 | -3,608 | | |
| | Exit | 0,250 | 0,050 | 0,250 | -0,003 | 589,000 | 1 | -1,841 | | |
| **Roof** | Corrugated fibre cement | 2,600 | 1,070 | 0,010 | 0,028 | 1400,000 | 2 | 77,896 | 77,896 | |
| **Ramp** | Steel walkway | - | - | - | - | - | 1 | 10,000 | 10,000 | |
| **Inhabitants** | Beaver adult | - | - | - | - | 25,000 | 2 | 50,000 | 130,000 | |
| | Beaver kit 1 | - | - | - | - | 20,000 | 2 | 40,000 | | |
| | Beaver kit 2 | - | - | - | - | 15,000 | 2 | 30,000 | | |
| | Beaver kit 3 | - | - | - | - | 5,000 | 2 | 10,000 | | |

*II. Centre of gravity*

| CG: Z-axis | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **Element** | **Lever (m)** | **Weight (N)** | **Moment (Nm)** | **CG (m)** | **CG: floats + refuge (m)** | **CG: refuge + beavers (m)** | **Composite CG (m)** |
| **Floats** | Reinforced EPS cutouts | 0,155 | 2086,890 | 323,468 | 0,219 | 0,441 | - | 0,459 |
| | Iron plate | 0,303 | 1601,522 | 484,460 | | | | |
| **Platform** | Top joist | 0,355 | 144,452 | 51,281 | 0,623 | | 0,613 | |
| | Bottom joist | 0,255 | 112,673 | 28,732 | | | | |
| | Deck board | 0,420 | 946,451 | 397,509 | | | | |
| | Joist header 1 | 0,305 | 433,357 | 132,174 | | | | |
| | Joist header 2 | 0,305 | 242,680 | 74,017 | | | | |
| **Walls** | Back | 0,685 | 361,131 | 247,374 | | | | |
| | Front | 0,685 | 346,685 | 237,479 | | | | |
| | Inner 1 | 0,740 | 185,043 | 136,932 | | | | |
| | Inner 2 | 0,740 | 185,043 | 136,932 | | | | |
| | Left | 0,740 | 370,087 | 273,864 | | | | |
| | Right | 0,740 | 370,087 | 273,864 | | | | |
| | Entrance | 0,610 | -35,391 | -21,588 | | | | |
| | Exit | 0,560 | -18,057 | -10,112 | | | | |
| **Roof** | Corrugated fibre cement | 1,062 | 764,160 | 811,538 | | | | |
| **Ramp** | Steel walkway | 0,380 | 98,100 | 37,278 | | | | |
| **Inhabitants** | Beaver 1 | 0,605 | 490,500 | 296,753 | 0,576 | - | | |
| | Beaver 2 | 0,574 | 392,400 | 225,238 | | | | |
| | Beaver 3 | 0,550 | 294,300 | 161,865 | | | | |
| | Beaver 4 | 0,520 | 98,100 | 51,012 | | | | |

| CG: Y-axis | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Component** | **Element** | **Lever (m)** | **Weight (N)** | **Moment (Nm)** | **CG (m)** | **CG: floats + refuge (m)** | **CG: refuge + beavers (m)** | **Composite CG (m)** |
| **Floats** | Reinforced EPS cutout 1 | 0,294 | 417,378 | 122,626 | 1,300 | 1,300 | - | 1,292 |
| | Iron plate 1 | 0,294 | 320,304 | 94,105 | | | | |
| | Reinforced EPS cutout 2 | 0,800 | 417,378 | 333,902 | | | | |
| | Iron plate 2 | 0,800 | 320,304 | 256,243 | | | | |
| | Reinforced EPS cutout 3 | 1,300 | 417,378 | 542,591 | | | | |
| | Iron plate 3 | 1,300 | 320,304 | 416,396 | | | | |
| | Reinforced EPS cutout 4 | 1,800 | 417,378 | 751,281 | | | | |
| | Iron plate 4 | 1,800 | 320,304 | 576,548 | | | | |
| | Reinforced EPS cutout 5 | 2,306 | 417,378 | 962,599 | | | | |
| | Iron plate 5 | 2,306 | 320,304 | 738,718 | | | | |
| **Platform** | Top joist | 1,300 | 144,452 | 187,788 | 1,300 | | 1,287 | |
| | Bottom joist 1 | 0,550 | 28,168 | 15,493 | | | | |
| | Bottom joist 2 | 1,050 | 28,168 | 29,577 | | | | |
| | Bottom joist 3 | 1,550 | 28,168 | 43,661 | | | | |
| | Bottom joist 4 | 2,050 | 28,168 | 57,745 | | | | |
| | Deck board | 1,300 | 946,451 | 1230,386 | | | | |
| | Joist header 1 | 0,025 | 121,340 | 3,033 | | | | |
| | Joist header 2 | 1,300 | 433,357 | 563,364 | | | | |
| | Joist header 3 | 2,575 | 121,340 | 312,450 | | | | |
| **Walls** | Back | 1,300 | 361,131 | 469,470 | | | | |
| | Front | 1,300 | 346,685 | 450,691 | | | | |
| | Inner 1 | 0,525 | 185,043 | 97,148 | | | | |
| | Inner 2 | 1,875 | 185,043 | 346,956 | | | | |
| | Left | 0,025 | 370,087 | 9,252 | | | | |
| | Right | 2,575 | 370,087 | 952,973 | | | | |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Entrance | 2,225 | -35,391 | -78,745 | | | | |
| | Exit | 0,275 | -18,057 | -4,966 | | | | |
| **Roof** | Corrugated fibre cement | 1,300 | 764,160 | 993,408 | | | | |
| **Ramp** | Steel walkway | 1,813 | 98,100 | 177,855 | | | | |
| **Inhabitants** | Beaver 1 | 0,938 | 637,650 | 598,307 | 1,241 | - | | |
| | Beaver 2 | 1,543 | 637,650 | 983,830 | | | | |

| **CG: X-axis** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Component** | **Element** | **Lever (m)** | **Weight (N)** | **Moment (Nm)** | **CG (m)** | **CG: floats + refuge (m)** | **CG: refuge + beavers (m)** | **Composite CG (m)** |
| **Floats** | Reinforced EPS cutout 1 | 0,538 | 1043,445 | 560,852 | 1,050 | 1,046 | - | 0,965 |
| | Iron plate 1 | 0,538 | 800,761 | 430,409 | | | | |
| | Reinforced EPS cutout 2 | 1,563 | 1043,445 | 1630,383 | | | | |
| | Iron plate 1 | 1,563 | 800,761 | 1251,189 | | | | |
| **Platform** | Top joist 1 | 0,375 | 36,113 | 13,542 | 1,042 | | 0,910 | |
| | Top joist 2 | 0,700 | 36,113 | 25,279 | | | | |
| | Top joist 3 | 1,400 | 36,113 | 50,558 | | | | |
| | Top joist 4 | 1,725 | 36,113 | 62,295 | | | | |
| | Bottom joist 1 | 0,538 | 56,336 | 30,281 | | | | |
| | Bottom joist 2 | 1,563 | 56,336 | 88,026 | | | | |
| | Deck board | 1,050 | 946,451 | 993,774 | | | | |
| | Joist header 1 | 0,025 | 144,452 | 3,611 | | | | |
| | Joist header 2 | 1,050 | 144,45225 | 151,675 | | | | |
| | Joist header 3 | 2,075 | 144,45225 | 503,561 | | | | |
| | Joist header 4 | 1,050 | 242,680 | 254,814 | | | | |
| **Walls** | Back | 2,075 | 361,131 | 749,346 | | | | |
| | Front | 0,025 | 346,685 | 8,667 | | | | |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Inner 1 | 0,525 | 185,043 | 97,148 | | | | |
| | Inner 2 | 0,525 | 185,043 | 97,148 | | | | |
| | Left | 1,050 | 370,087 | 388,591 | | | | |
| | Right | 1,050 | 370,087 | 388,591 | | | | |
| | Entrance | 0,025 | -35,391 | -0,885 | | | | |
| | Exit | 0,025 | -18,057 | -0,451 | | | | |
| **Roof** | Corrugated fibre cement | 1,050 | 764,160 | 802,368 | | | | |
| **Ramp** | Steel walkway | -0,125 | 98,100 | -12,263 | | | | |
| **Inhabitants** | Beaver 1 | 0,230 | 490,500 | 113,011 | 0,444 | - | | |
| | Beaver 2 | 0,460 | 392,400 | 180,661 | | | | |
| | Beaver 3 | 0,657 | 294,300 | 193,355 | | | | |
| | Beaver 4 | 0,810 | 98,100 | 79,461 | | | | |

### *III. Buoyancy*

| | |
|---|---|
| **Buoyant force (no load; N)** | 3688,41 |
| **Buoyant force (full load; N)** | 9470,21 |
| **Max buoyancy (floats submerged; N)** | 12730,04 |

| **1. FLOATS** | | | | |
|---|---|---|---|---|
| **Mass (kg)** | **Volume ($m^3$)** | **Contact area ($m^2$)** | **Draft (m)** | **Freeboard (m)** |
| **375,985** | 0,376 | 4,186 | 0,0898 | 0,345 |

Centre of buoyancy = centre of gravity of displaced water

| | **Shape** | **Lever (m)** | **Length (m)** | **Width (m)** | **Height (m)** | **Unit weight (kg/m3)** | **Quantity** | **Weight (N)** | **Moment (Nm)** | **CB (m)** |
|---|---|---|---|---|---|---|---|---|---|---|
| **Z axis** | EPS | 0,045 | 0,910 | 0,460 | 0,090 | 1000 | 10 | 3688,412 | 165,646 | *0,045* |
| **Y axis** | EPS 1 | 0,294 | 0,910 | 0,460 | 0,090 | 1000 | 2 | 737,682 | 216,731 | *1,300* |
| | EPS 2 | 0,800 | 0,910 | 0,460 | 0,090 | 1000 | 2 | 737,682 | 590,146 | |
| | EPS 3 | 1,300 | 0,910 | 0,460 | 0,090 | 1000 | 2 | 737,682 | 958,987 | |
| | EPS 4 | 1,800 | 0,910 | 0,460 | 0,090 | 1000 | 2 | 737,682 | 1327,828 | |
| | EPS 5 | 2,306 | 0,910 | 0,460 | 0,090 | 1000 | 2 | 737,682 | 1701,317 | |
| **X axis** | EPS 1 | 0,538 | 0,910 | 0,460 | 0,090 | 1000 | 5 | 1844,206 | 991,261 | *1,050* |
| | EPS 2 | 1,563 | 0,910 | 0,460 | 0,090 | 1000 | 5 | 1844,206 | 2881,572 | |

| **2. FLOATS + REFUGE LOAD** | | | | |
|---|---|---|---|---|
| **Mass (kg)** | **Volume ($m^3$)** | **Contact area ($m^2$)** | **Draft (m)** | **Freeboard (m)** |
| **835,363** | 0,835 | 4,186 | 0,1996 | 0,235 |

| | | **Y axis** | **X axis** |
|---|---|---|---|
| **Horizontal** | a | 0,000 | 0,008 |
| | m | 459,378 | 459,378 |
| | $\rho$ | 1000,000 | 1000,000 |
| | V0 | 0,376 | 0,376 |
| | B0Bh | 0,000 | 0,004 |
| **Vertical** | d | 0,110 | 0,110 |
| | m | 459,378 | 459,378 |
| | $\rho$ | 1000,000 | 1000,000 |
| | V0 | 0,376 | 0,376 |
| | B0Bv | 0,030 | 0,030 |

| | CB (m) |
|---|---|
| **Z axis** | *0,075* |
| **Y axis** | *1,300* |
| **X axis** | *1,046* |

| **3. FLOATS + REFUGE LOAD + BEAVER LOAD** | | | | |
|---|---|---|---|---|
| **Mass (kg)** | **Volume ($m^3$)** | **Contact area ($m^2$)** | **Draft (m)** | **Freeboard (m)** |
| **965,363** | 0,965 | 4,186 | 0,2306 | 0,204 |

| | | Y axis | X axis |
|---|---|---|---|
| **Horizontal** | a | 0,013 | 0,140 |
| | m | 589,378 | 589,378 |
| | $\rho$ | 1000,000 | 1000,000 |
| | V0 | 0,376 | 0,376 |
| | B0Bh | 0,008 | 0,085 |
| **Vertical** | d | 0,141 | 0,141 |
| | m | 589,378 | 589,378 |
| | $\rho$ | 1000,000 | 1000,000 |
| | V0 | 0,376 | 0,376 |
| | B0Bv | 0,043 | 0,043 |

| | CB (m) |
|---|---|
| **Z axis** | *0,088* |
| **Y axis** | *1,292* |
| **X axis** | *0,965* |

### *IV. Metacentre*

| | | **l** | **b** | **d** | **V** | **i** | **OB** | **OG** | **MB** | **OM** | **MG** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **FLOATS** | Y axis | 1,820 | 2,300 | 0,090 | 0,376 | 1,845 | 0,045 | 0,219 | 4,908 | 4,953 | *4,734* |
| | X axis | 2,300 | 1,820 | 0,090 | 0,376 | 1,155 | 0,045 | 0,219 | 3,073 | 3,118 | *2,899* |
| **REFUGE LOAD** | Y axis | 1,820 | 2,300 | 0,200 | 0,835 | 1,845 | 0,100 | 0,441 | 2,209 | 2,309 | *1,868* |
| | X axis | 2,300 | 1,820 | 0,200 | 0,835 | 1,155 | 0,100 | 0,441 | 1,383 | 1,483 | *1,042* |
| **REFUGE LOAD + BEAVER LOAD** | Y axis | 1,820 | 2,300 | 0,231 | 0,965 | 1,845 | 0,115 | 0,459 | 1,912 | 2,027 | *1,568* |
| | X axis | 2,300 | 1,820 | 0,231 | 0,965 | 1,155 | 0,115 | 0,459 | 1,197 | 1,312 | *0,853* |

## V. Tilt

| REFUGE LOAD | | | |
|---|---|---|---|
| Y axis | | X axis | |
| **G0G1** | 0,0001 | G0G1 | 0,0044 |
| **MG0** | 1,8676 | MG0 | 1,0418 |
| **ϕ** | 0,0038 | ϕ | 0,2426 |
| **b** | 1,9350 | b | 1,9350 |
| **z** | 0,0001 | z | 0,0041 |

| REFUGE LOAD + BEAVER LOAD | | | |
|---|---|---|---|
| Y axis | | X axis | |
| **G0G1** | 0,0081 | G0G1 | 0,0854 |
| **MG0** | 1,5675 | MG0 | 0,8529 |
| **ϕ** | 0,2963 | ϕ | 5,7177 |
| **b** | 1,9350 | b | 1,9350 |
| **z** | 0,0050 | z | 0,1042 |

## VI. Wave forces

| | 3_1 | 4_4 | 5b_2 |
|---|---|---|---|
| $\rho$ | 1000 | 1000 | 1000 |
| **g** | 9,810 | 9,810 | 9,810 |
| **Hi** | 0,970 | 0,780 | 0,890 |
| **d** | 0,231 | 0,231 | 0,231 |
| **dt** | -0,739 | -0,549 | -0,659 |
| **Fmax** | 4389 | 3529 | 4027 |
| **Arm** | 0,400 | 0,337 | 0,374 |
| **Moment** | 1756 | 1189 | 1504 |

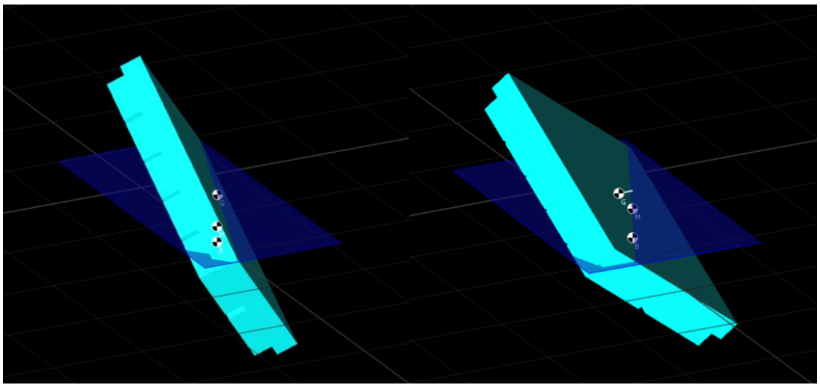
| | | | |
|---|---|---|---|
| **Buoyancy** | 9470 | 9470 | 9470 |
| **GZ** | 0,1855 | 0,1255 | 0,1588 |

### VII. GZ curve

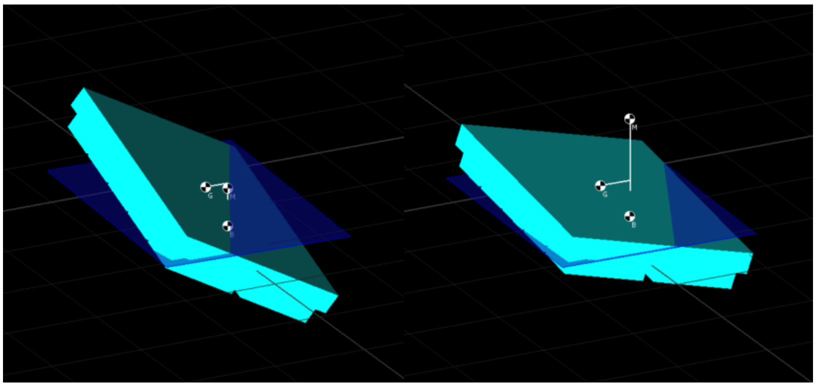
GZ curve animation – https://vimeo.com/721035948

| Heel [°] | GZ [m] | GZ Area [m*rad] | TR [m] | Displacement [tonnes] | Ta [m] | Tf [m] |
|---|---|---|---|---|---|---|
| **-75,9** | 0,147 | 0 | 1,646 | 0,965 | -0,687 | 0,959 |
| **-70,6** | 0,114 | 0 | 1,624 | 0,965 | -0,662 | 0,962 |
| **-65,2** | 0,077 | 0 | 1,576 | 0,965 | -0,624 | 0,952 |
| **-59** | 0,029 | 0 | 1,484 | 0,965 | -0,564 | 0,921 |
| **-53,6** | -0,017 | 0 | 1,376 | 0,965 | -0,497 | 0,879 |
| **-45,6** | -0,095 | 0 | 1,164 | 0,965 | -0,373 | 0,791 |
| **-40,4** | -0,148 | 0 | 1,006 | 0,965 | -0,285 | 0,721 |
| **-33,2** | -0,22 | 0 | 0,775 | 0,965 | -0,16 | 0,615 |
| **-31** | -0,241 | 0 | 0,704 | 0,965 | -0,123 | 0,582 |
| **-25,5** | -0,285 | 0 | 0,546 | 0,965 | -0,04 | 0,506 |
| **-20,2** | -0,324 | 0 | 0,408 | 0,965 | 0,03 | 0,438 |
| **-18,2** | -0,33 | 0 | 0,358 | 0,965 | 0,055 | 0,413 |
| **-15,1** | -0,328 | 0 | 0,292 | 0,965 | 0,088 | 0,381 |
| **-10** | -0,294 | 0 | 0,213 | 0,965 | 0,129 | 0,343 |
| **-8** | -0,268 | 0 | 0,196 | 0,965 | 0,14 | 0,335 |
| **-5** | -0,202 | 0 | 0,18 | 0,965 | 0,151 | 0,331 |
| **-3** | -0,153 | 0 | 0,175 | 0,965 | 0,156 | 0,33 |
| **0** | 0,056 | 0 | 0,164 | 0,965 | 0,164 | 0,328 |
| **3** | 0,128 | 0 | 0,155 | 0,965 | 0,162 | 0,316 |
| **5** | 0,17 | 0 | 0,141 | 0,965 | 0,162 | 0,304 |
| **8** | 0,228 | 0 | 0,117 | 0,965 | 0,164 | 0,281 |
| **10** | 0,265 | 0 | 0,101 | 0,965 | 0,165 | 0,265 |
| **15** | 0,33 | 0 | 0,08 | 0,965 | 0,157 | 0,237 |
| **20** | 0,338 | 0 | 0,069 | 0,965 | 0,145 | 0,214 |
| **25** | 0,321 | 0 | 0,053 | 0,965 | 0,134 | 0,187 |
| **30** | 0,293 | 0 | 0,03 | 0,965 | 0,125 | 0,155 |
| **35** | 0,258 | 0 | -0,002 | 0,965 | 0,119 | 0,117 |
| **40** | 0,219 | 0 | -0,056 | 0,965 | 0,123 | 0,066 |
| **45** | 0,175 | 0 | -0,141 | 0,965 | 0,14 | -0,001 |
| **50,1** | 0,128 | 0 | -0,23 | 0,965 | 0,16 | -0,07 |
| **55,2** | 0,081 | 0 | -0,313 | 0,965 | 0,178 | -0,135 |
| **60,3** | 0,032 | 0 | -0,394 | 0,965 | 0,195 | -0,199 |
| **65,4** | -0,017 | 0 | -0,468 | 0,965 | 0,208 | -0,26 |
| **70,4** | -0,064 | 0 | -0,526 | 0,965 | 0,215 | -0,311 |

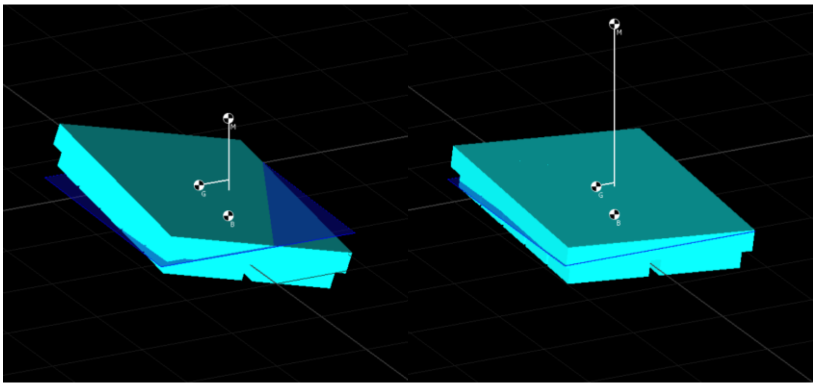
Figures corresponding to the platform's behaviour under different heeling angles are displayed on the following page.



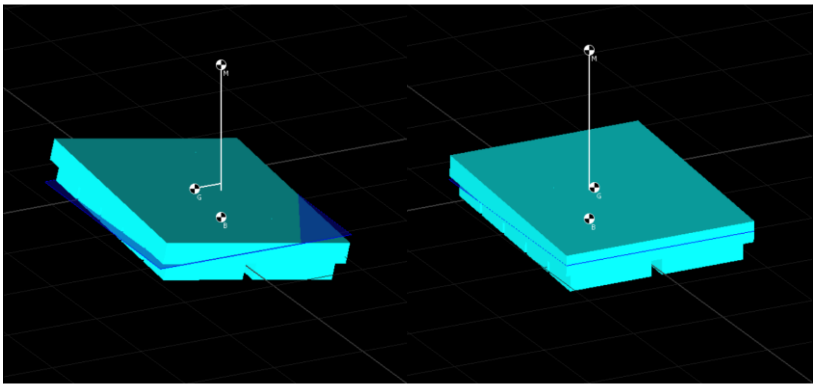
| | |
|---|---|
| -56° | -40° |



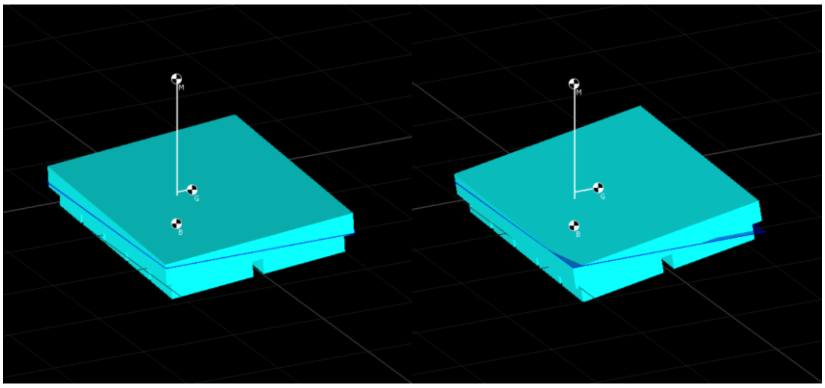
| | |
|---|---|
| -30° | -20° |



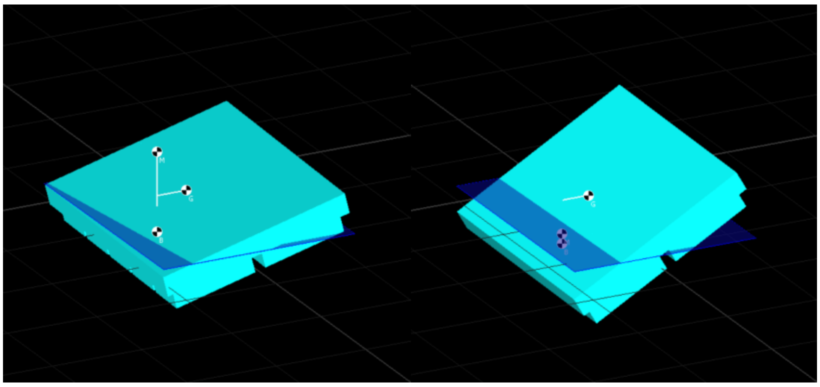
| | |
|---|---|
| -15° | -10° |



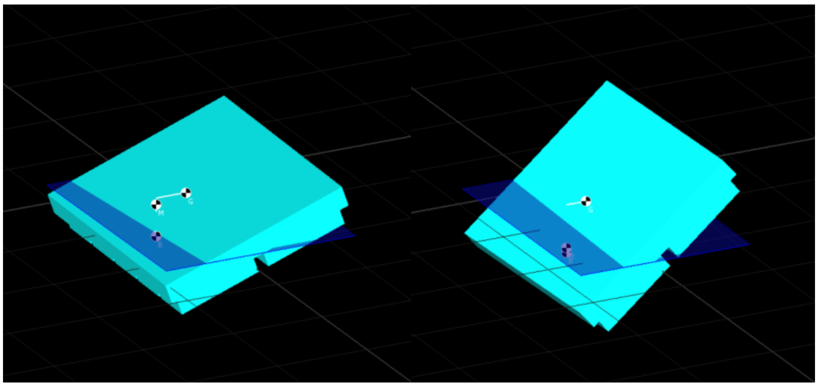
| | |
|---|---|
| -5° | 0° |



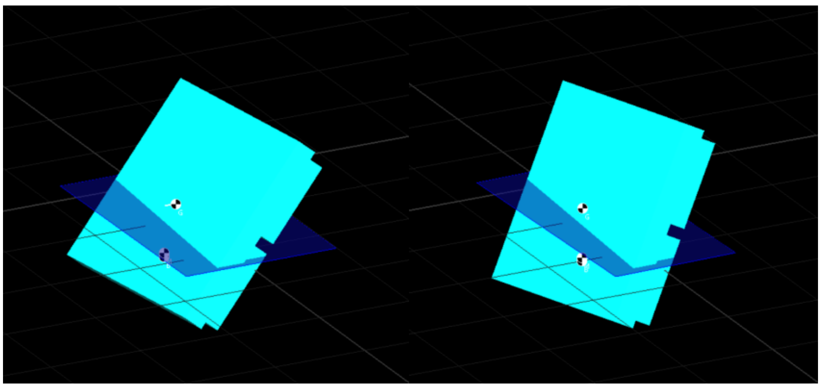
| | |
|---|---|
| 5° | 10° |



| | |
|---|---|
| 15° | 20° |

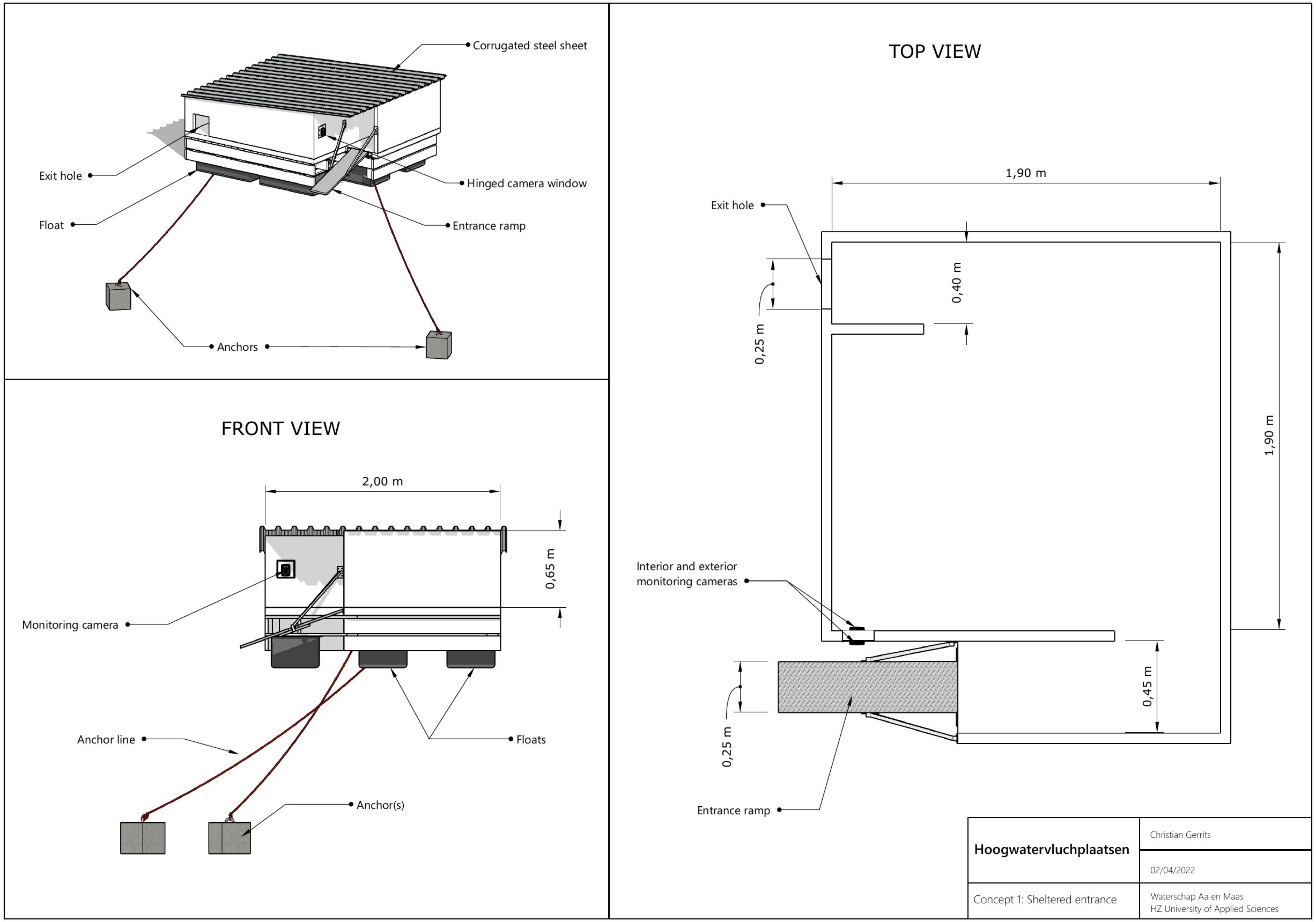


| | |
|---|---|
| 30° | 40° |

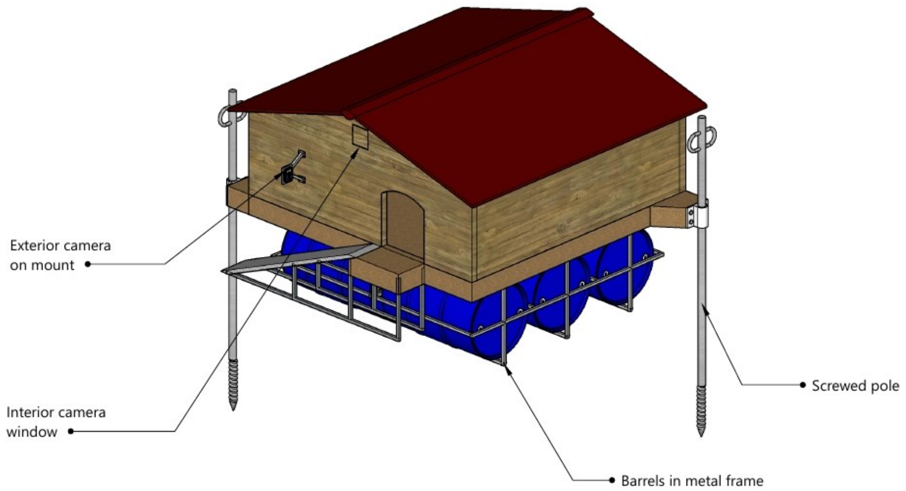


| | |
|---|---|
| 50° | 62° |

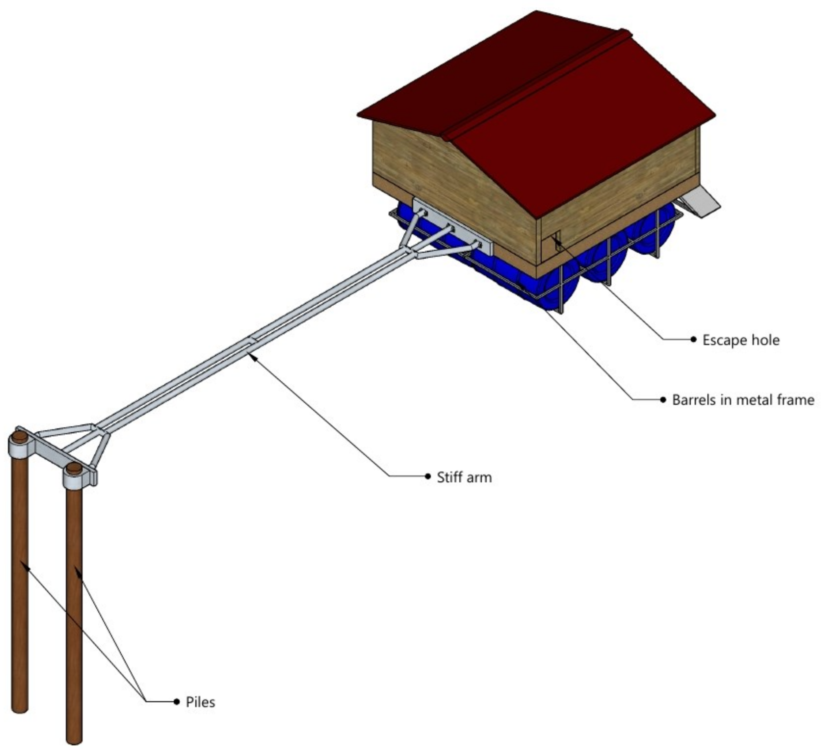
## E. Alternative designs



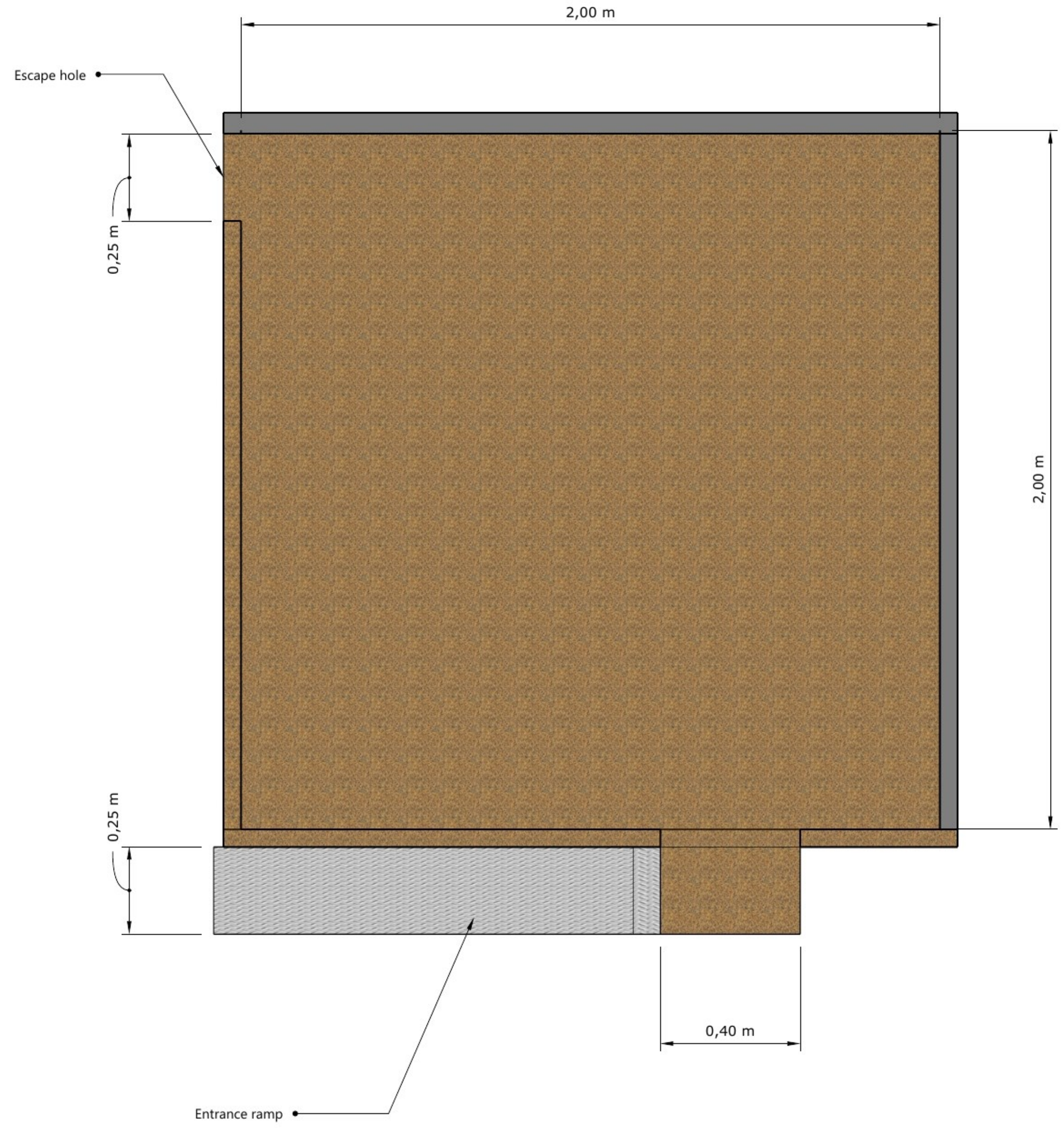
## ISOMETRIC VIEW - POLE STABILISATION




## ISOMETRIC VIEW - STIFF ARM STABILISATION

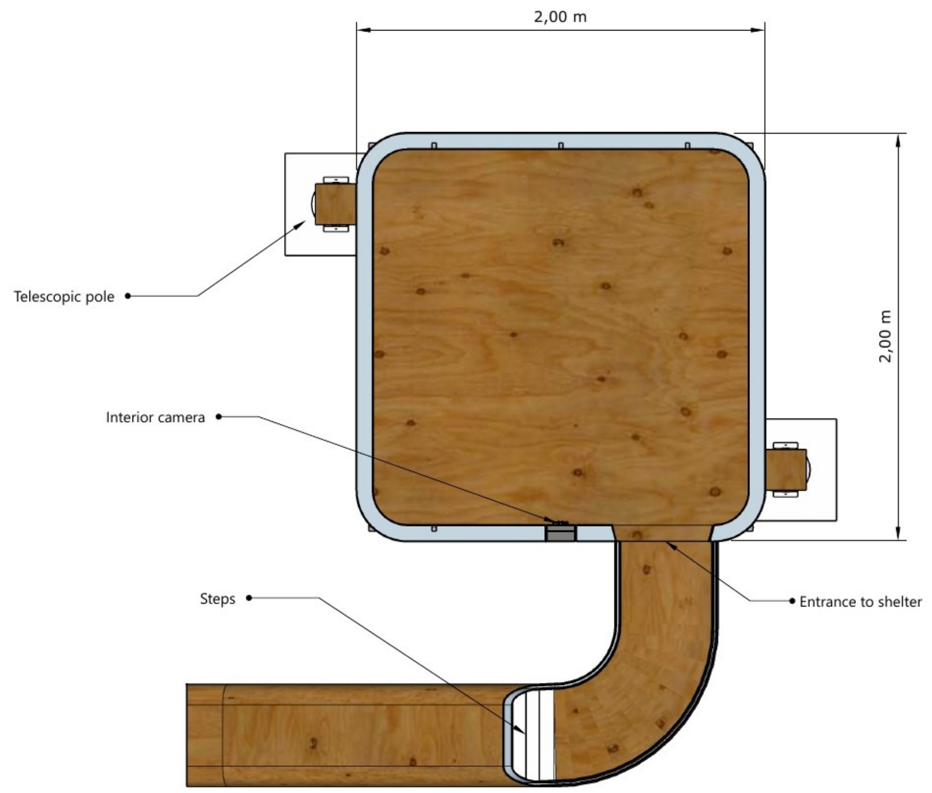



## TOP VIEW

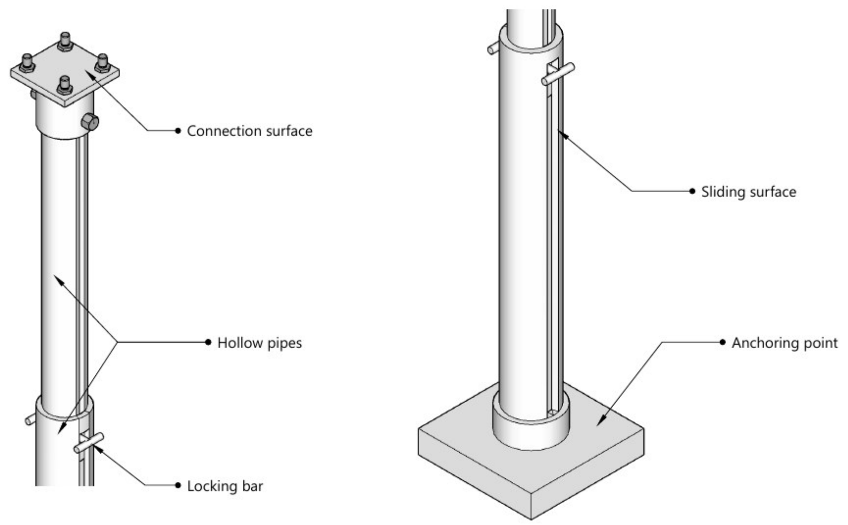



| | |
|---|---|
| **Hoogwatervluchplaatsen** | Christian Gerrits |
| | 08/04/2022 |
| Concept 2: Open entrance | Waterschap Aa en Maas<br>HZ University of Applied Sciences |

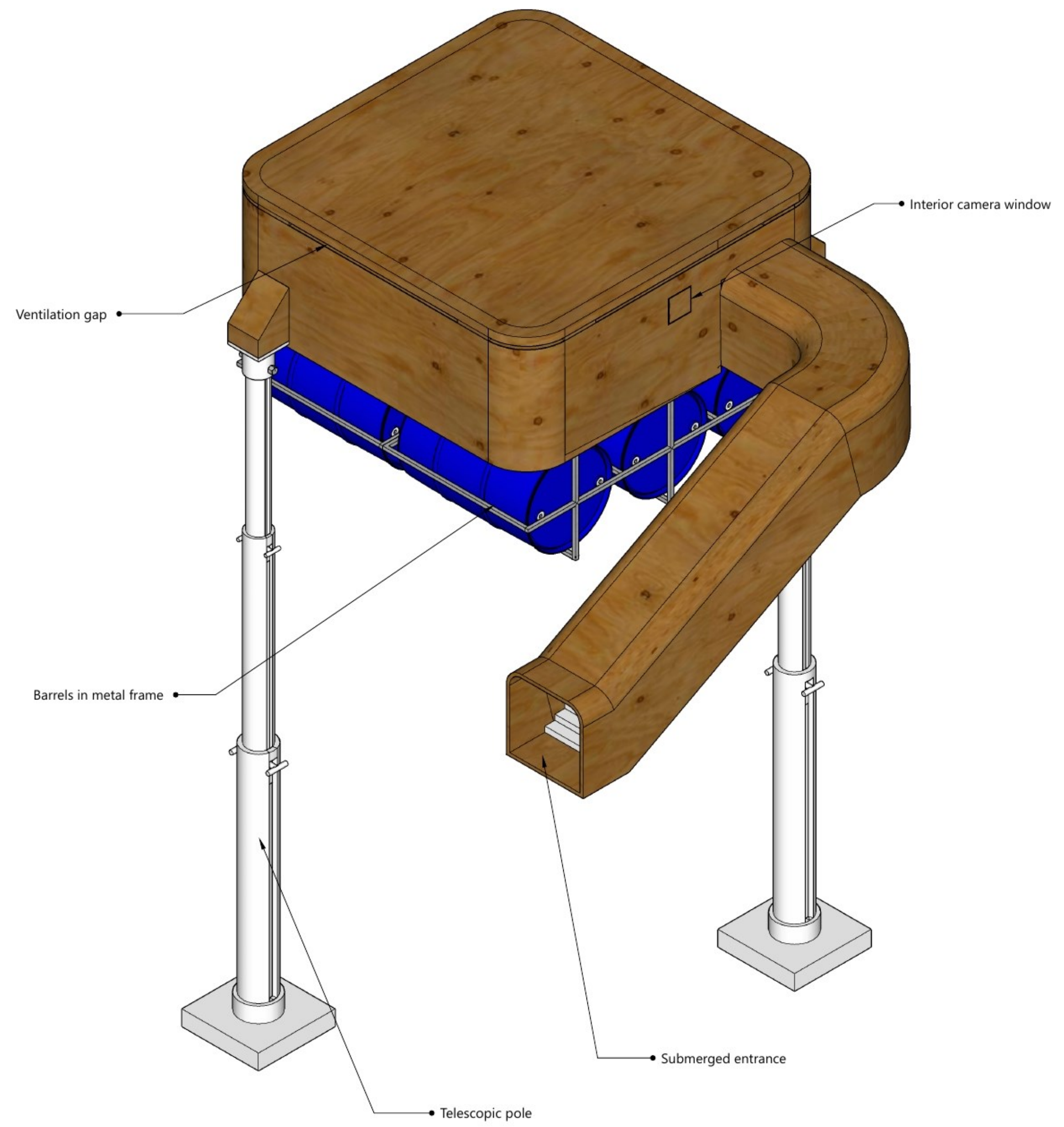
## TOP VIEW




## DETAIL - TELESCOPIC POLE

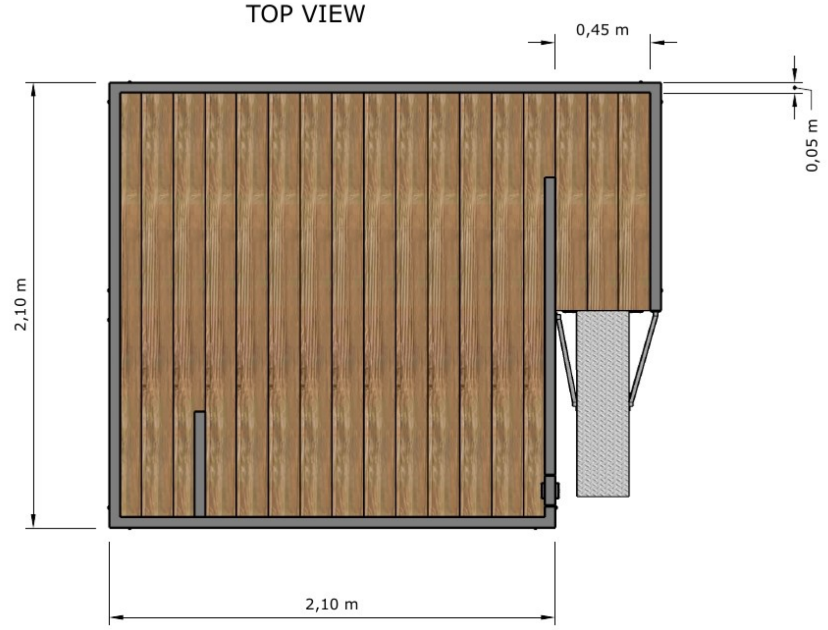



## ISOMETRIC VIEW - FRONT

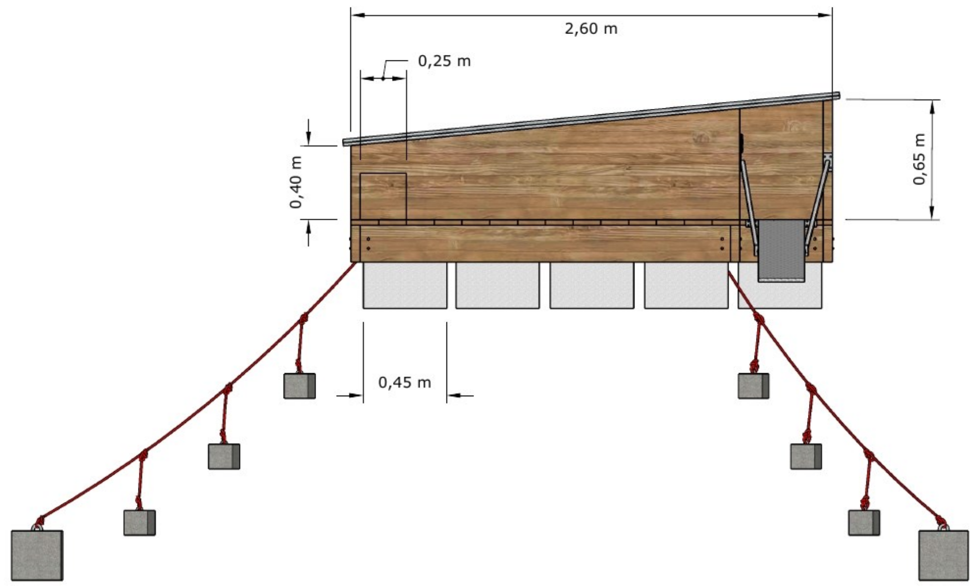



| | |
|---|---|
| **Hoogwatervluchplaatsen** | Christian Gerrits<br>08/04/2022 |
| Concept 3: Submerged entrance | Waterschap Aa en Maas<br>HZ University of Applied Sciences |

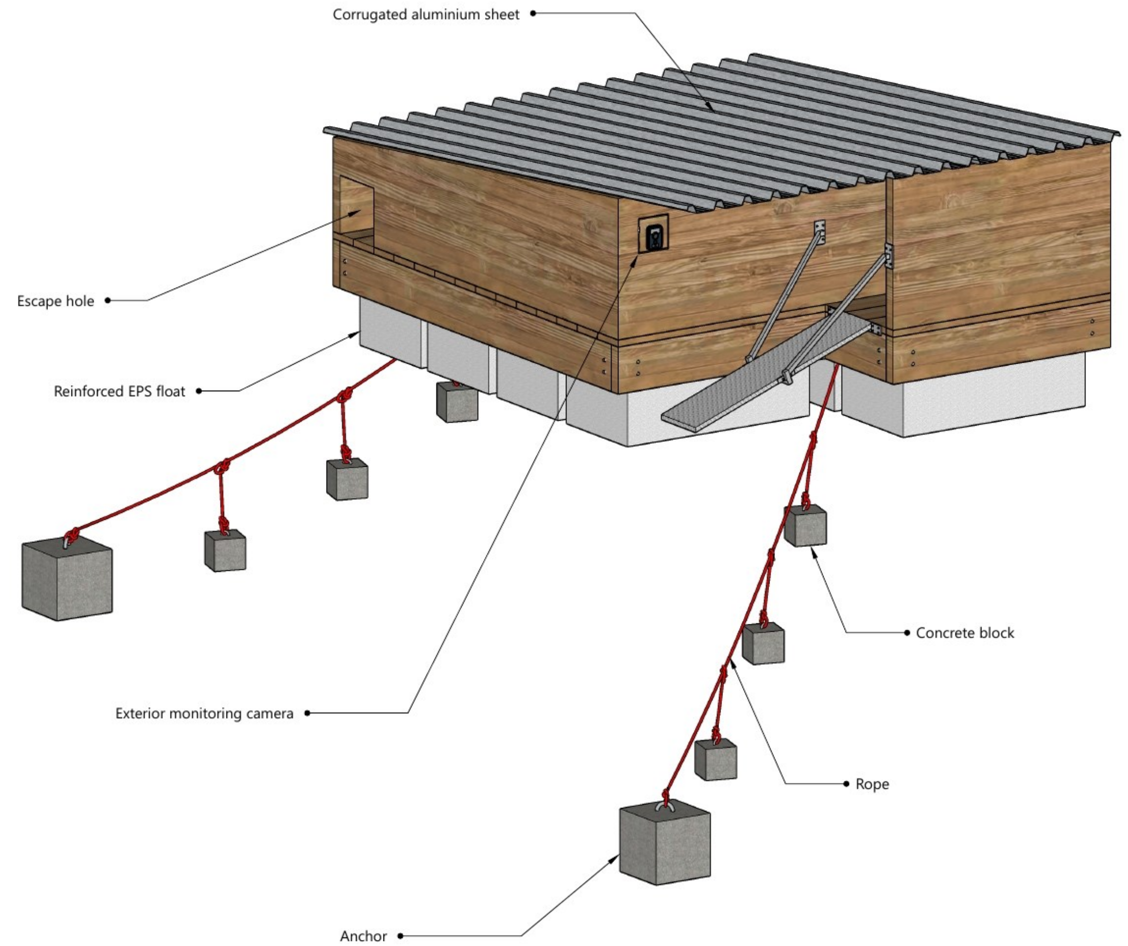
## TOP VIEW




## FRONT VIEW

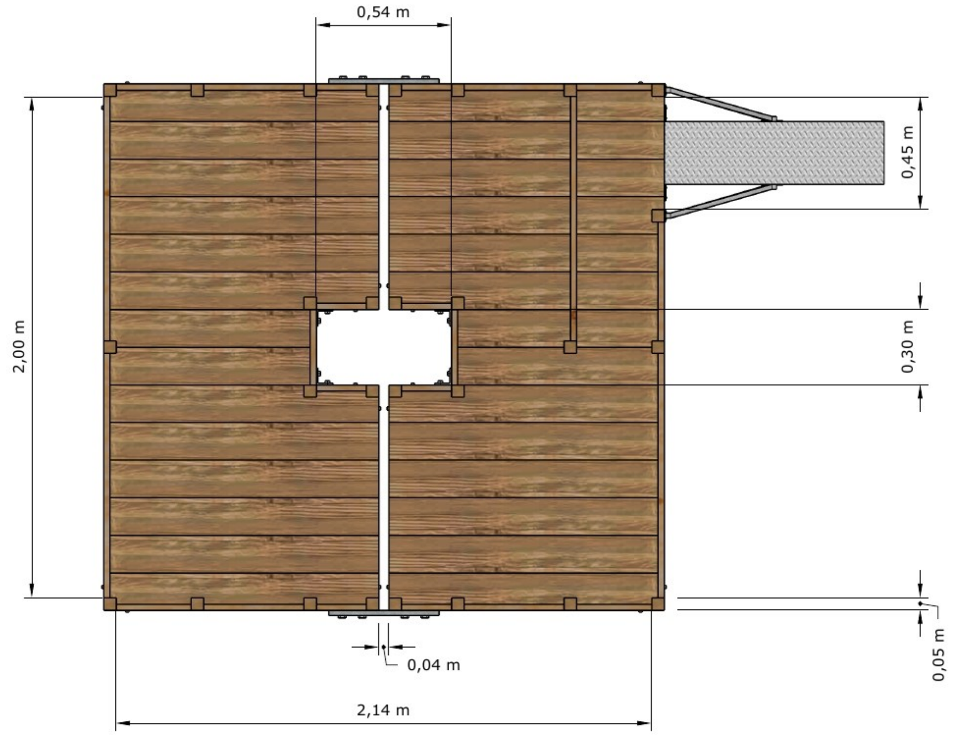



## ISOMETRIC VIEW

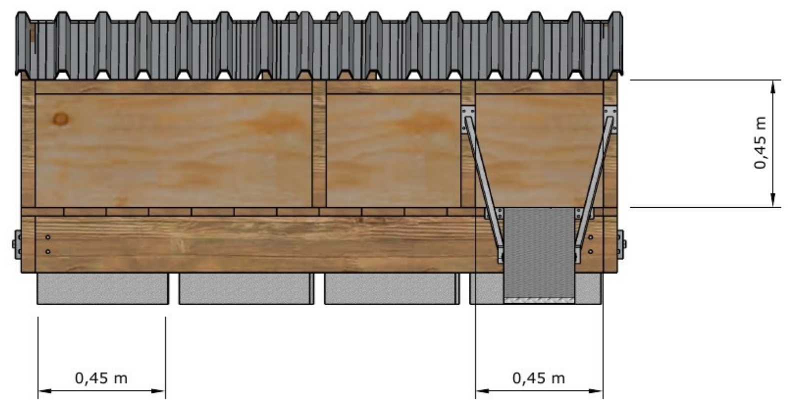



| | |
|---|---|
| **Hoogwatervluchtplaatsen** | Christian Gerrits |
| | 12/05/2022 |
| Concept 1: Sheltered entrance, weighted rope | Waterschap Aa en Maas<br>HZ University of Applied Sciences |

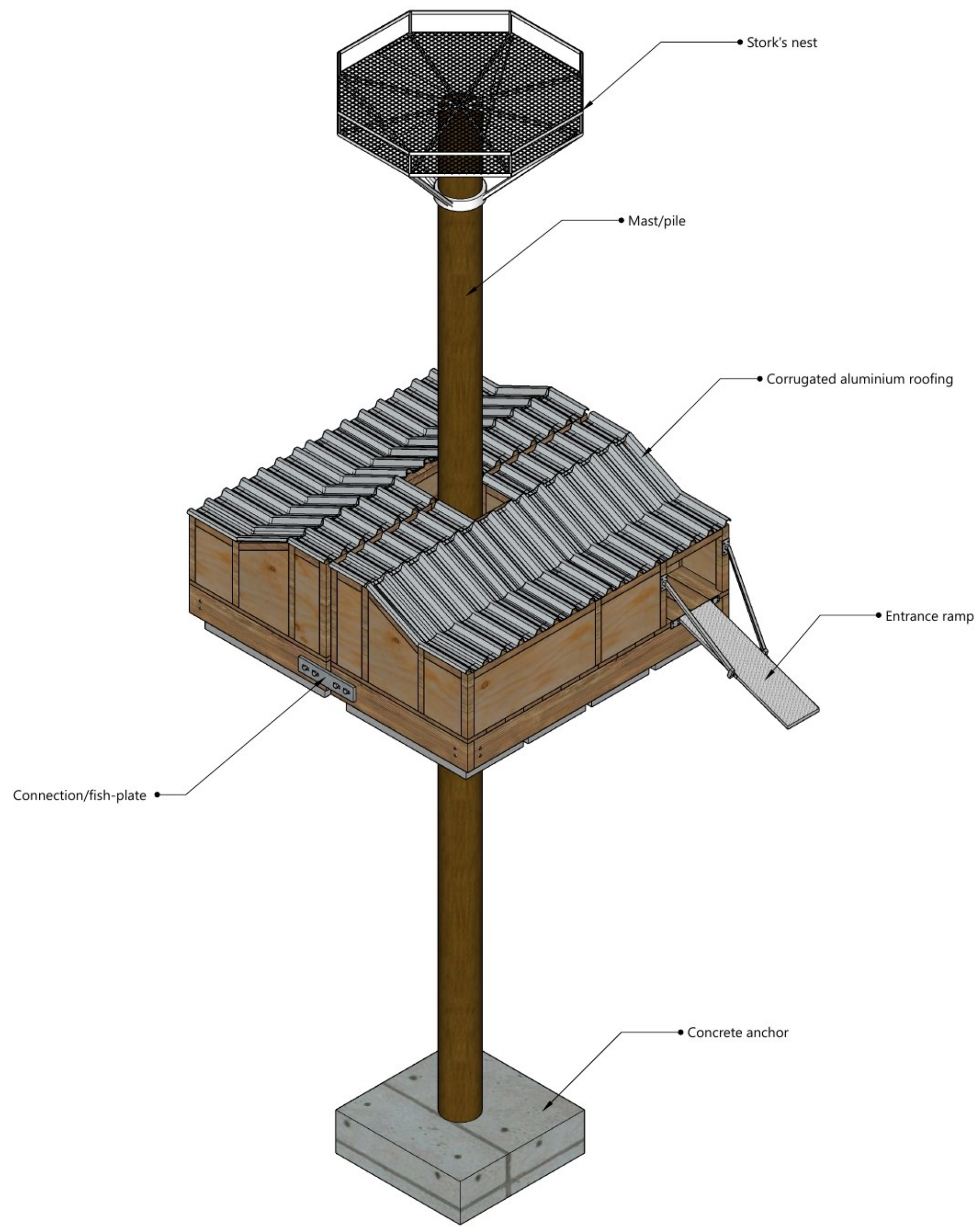
TOP VIEW




FRONT VIEW




ISOMETRIC VIEW

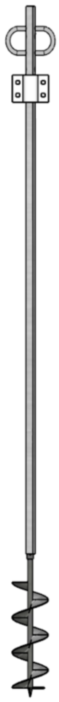


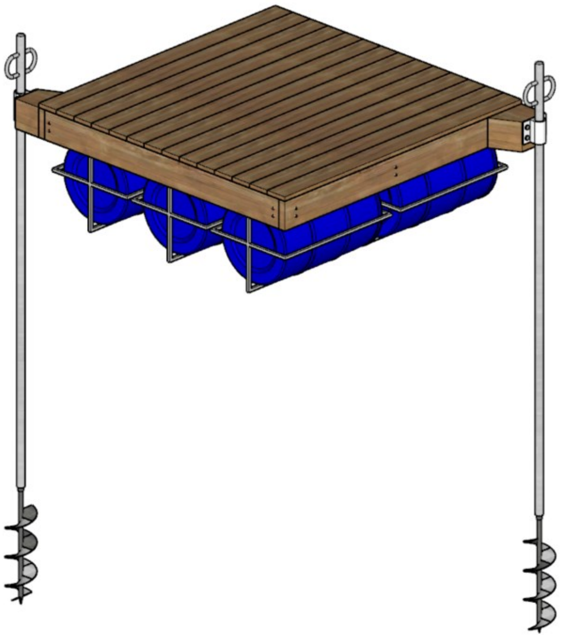

| | |
|---|---|
| **Hoogwatervluchplaatsen** | Christian Gerrits |
| | 12/05/2022 |
| Concept 2: Sheltered entrance, mast/pile | Waterschap Aa en Maas<br>HZ University of Applied Sciences |

## F. Anchorage mechanisms

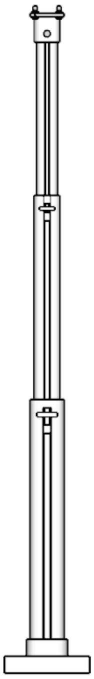
Hyperlink back to Chapter 5.1.2: Alternatives

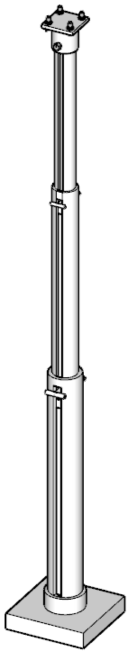
ii. Screwed poles

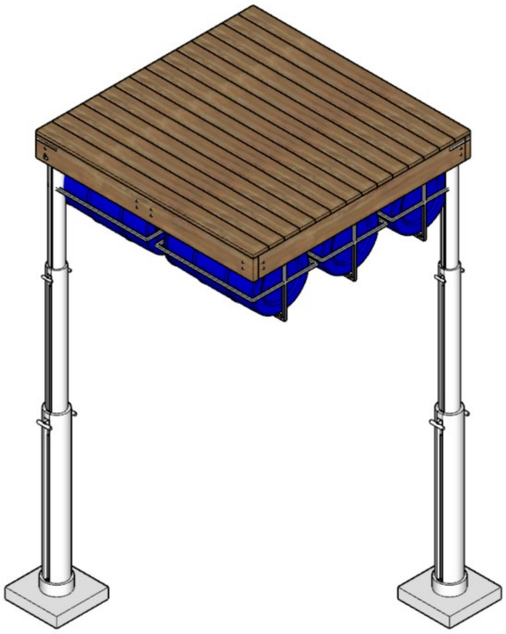




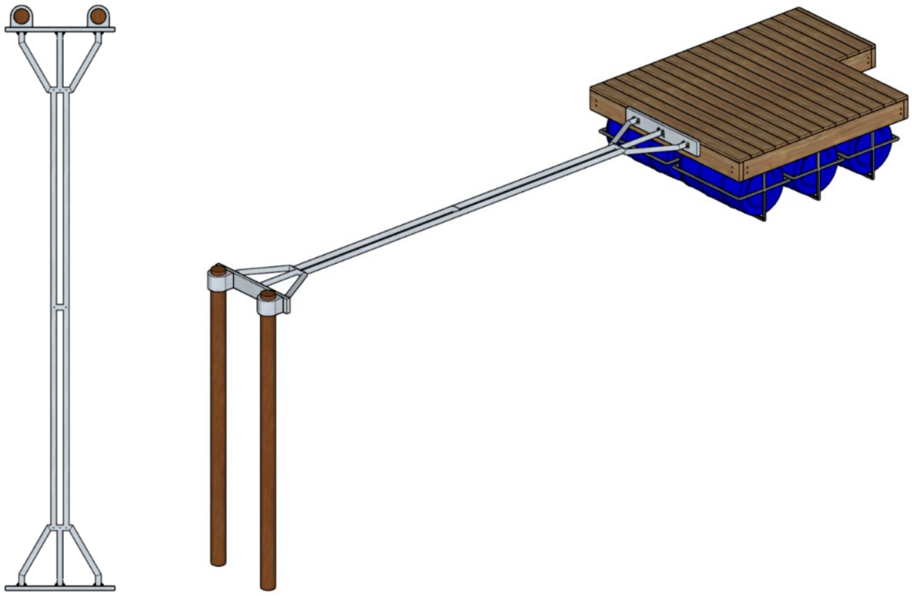
iii. Telescopic poles



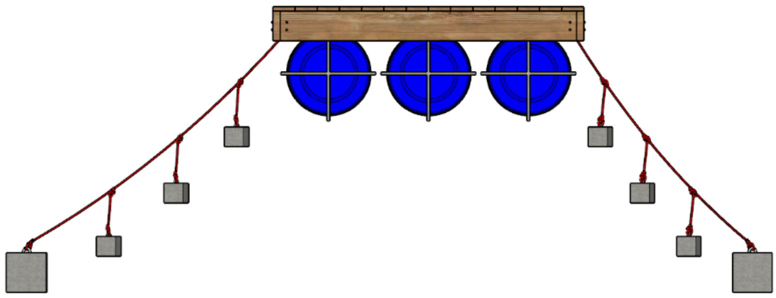


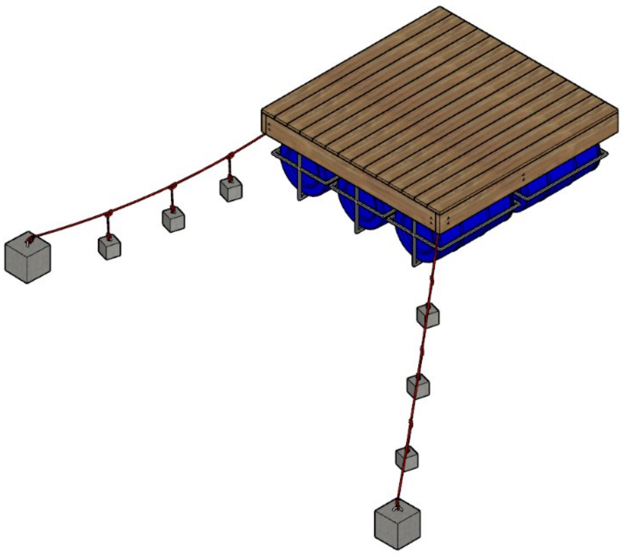


iv. Stiff arm

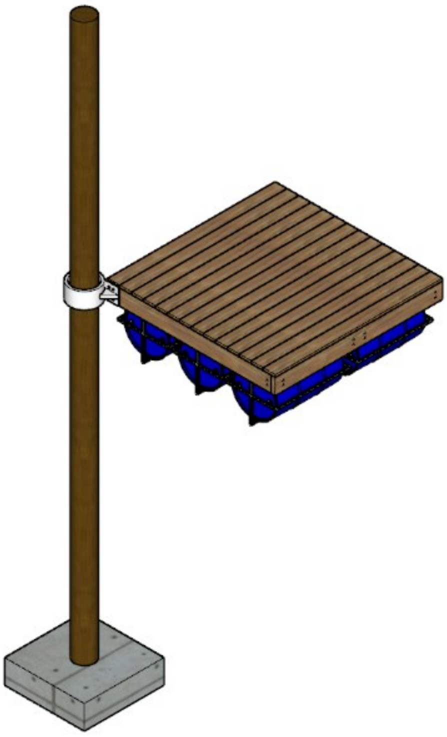


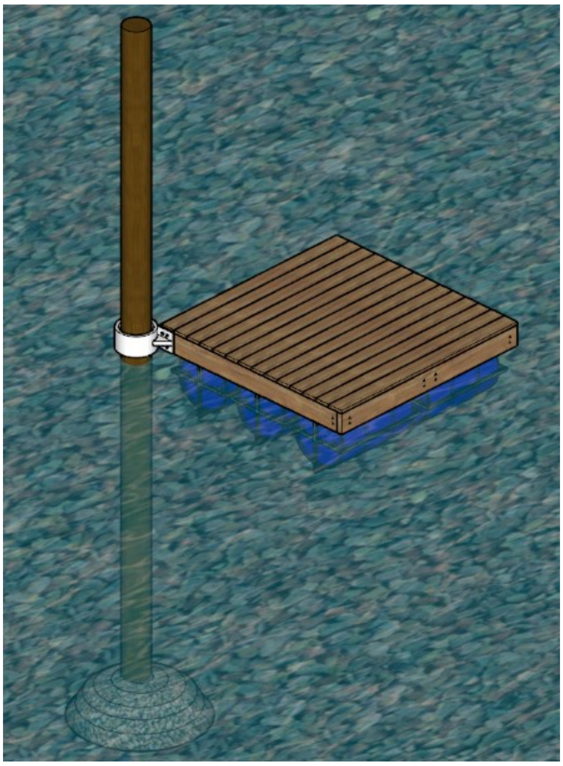
v. Weighted rope

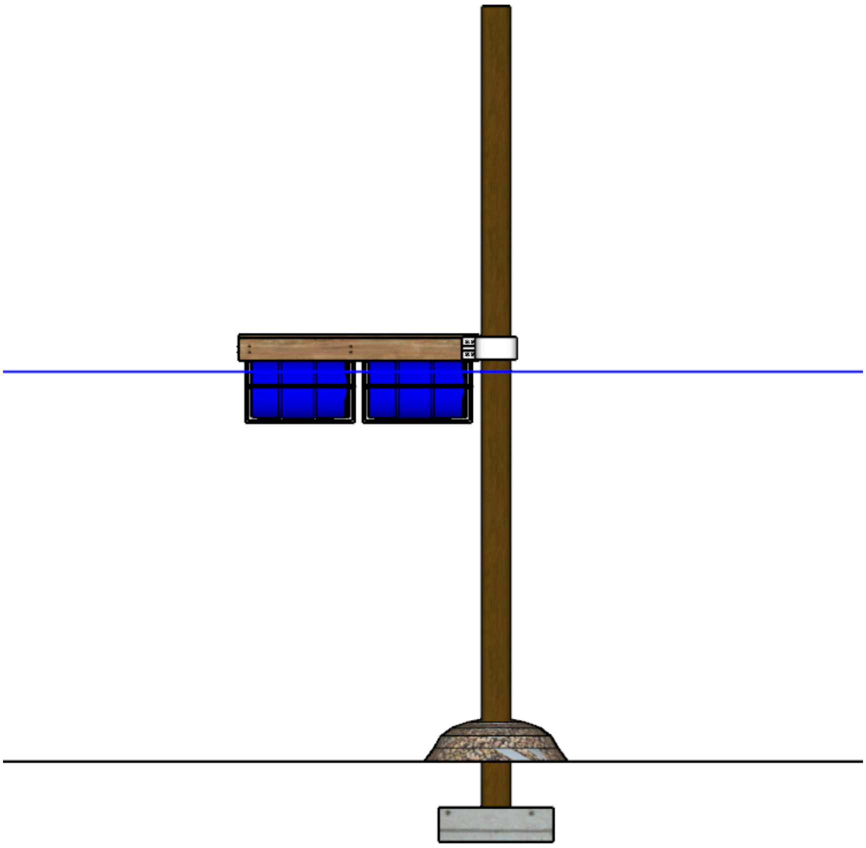




vi. Corner pile + collar







## F. Materials

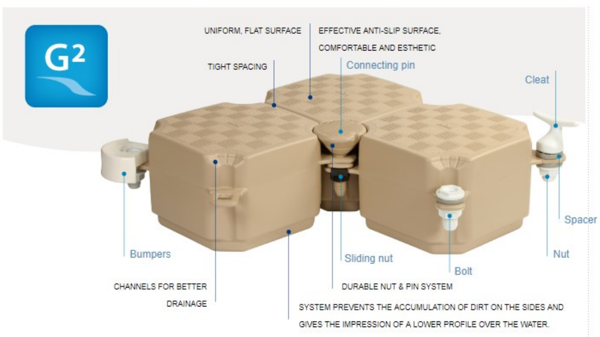
Hyperlink back to Chapter 5.1.2: Alternatives

Floats:

- Plastic barrels

- Reinforced polystyrene blocks

- Modular floats



Roof:

- Fibre cement sheets

- Wooden panels

- Aluminium sheets

Insulation:

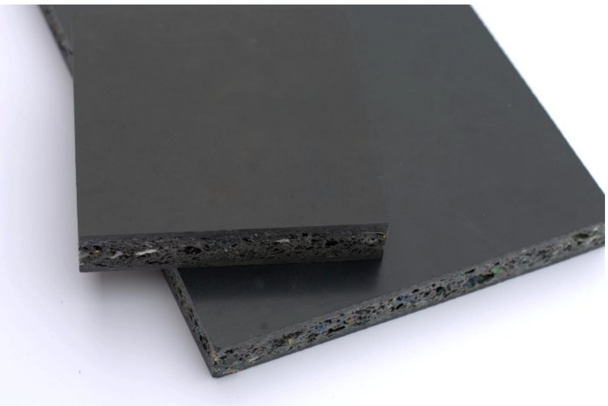
- Sprayed polyurethane foam

- Glass fibre

Platform + walls:

- Wooden boards

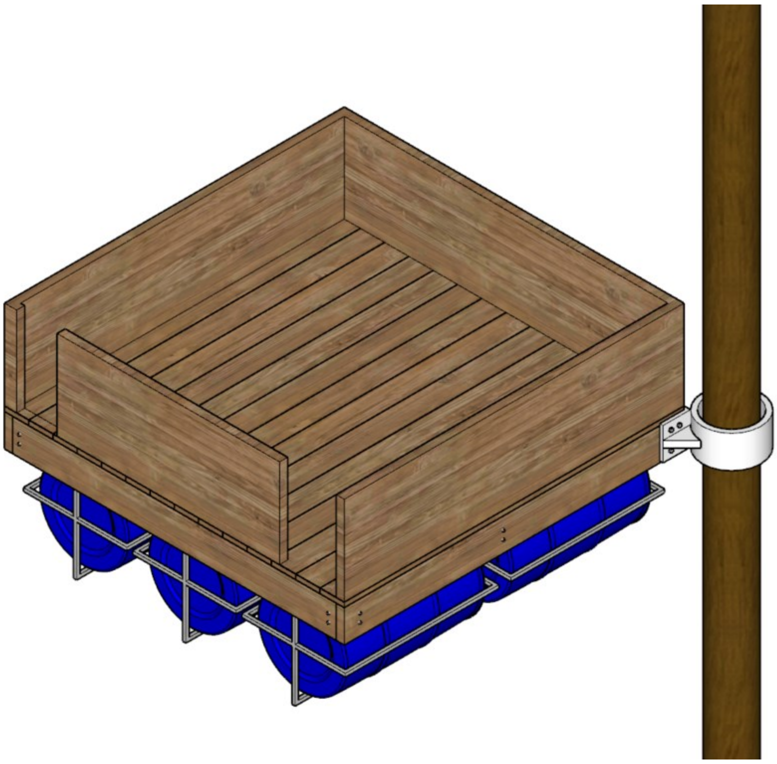
- Recycled plastic boards



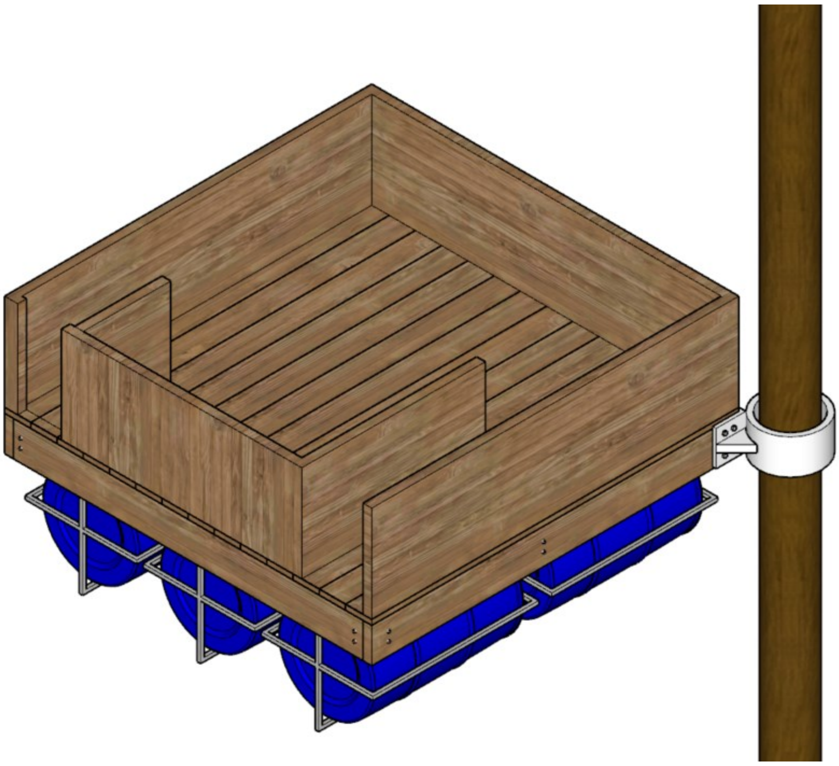
## G. Entrance types

Hyperlink back to Chapter 5.1.2: Alternatives

a. Open



b. Sheltered



c. Submerged