EVERY DROP COUNTS

How to keep the Rhine
functional in times of drought

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Every Drop Counts
How to keep the Rhine functional in times of drought

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* Cover image made by author

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ABSTRACT

More and more frequently, the streamflow of the Rhine becomes dangerously low. Drought is exacerbated by climate change, glaciers are melting at rapid rates. These problems affect the functions and ecosystems around the Rhine. The Rhine accounts for two-thirds of all inland waterway transports across Europe and thus experiences severe economic consequences when the streamflow gets low. Goods can no longer be shipped, and industries and agriculture depend on this water supply. More importantly, the Rhine also serves as a source of clean drinking water. With growing urbanisation, industries and agriculture along the Rhine, the pressure on the drinking water supply grows. The chances of periods of drought are increasing. Problems like salinisation, water pollution, damage to ecosystems and rising water temperatures will only become more apparent in the future.

In Every Drop Counts, the vision for the Rhine is to become a connected green-blue infrastructure. This proposal combines nature-based solutions that form a coherent system on a small scale and a green-blue infrastructure that works in a cross-border approach. Together they provide habitat diversity, mitigate drought, and human-nature interactions. The riverscape of the Rhine has to deal with more extreme fluctuations in water levels and more intense periods of drought and flooding. To battle the problems the Rhine faces, this thesis attempts to create a pattern catalogue focussing on drought-mitigating design strategies. These strategies are implemented around the Rhine to create a riverscape able to deal with streamflow fluctuations.

The design strategy will have other positive benefits besides a drought-resilient riverscape. Flooding of urbanised areas can be avoided, and living and recreational spaces will stay functional during periods of drought. Industries, agriculture and thus the economy around the Rhine will remain stable during periods of drought, as water retention capacity will be increased and buffers can be implemented.
Habitat diversity will develop and improve biodiversity. The implemented green-blue infrastructure creates a connected structure of habitats where species can flourish. Part of this strategy will be restoring historic riverscapes, creating more space for the Rhine and bringing back old habitats that got lost during the reconstruction of the Rhine.

To create a functional riverscape during streamflow drought, the Rhine will have to use all available water throughout the seasons. To mitigate the drought problems, the urban and rural areas have to create a synergy where strategies are combined, and land is optimally used to develop a drought-mitigating strategy. For this, it is essential to know what each area around the Rhine offers and what type of drought-mitigating measures are most suitable to implement.

The nature-based solutions embedded in the green-blue infrastructure are combined into a drought-mitigating pattern catalogue. This multiscalar pattern catalogue can be filtered for different types of landscapes, land uses, and more requirements. This approach is tested on other design locations and leads to a selection of measures that apply to different landscapes. By implementing the green-blue infrastructure approach with nature-based drought-mitigating solutions in rural and urban areas, a functional riverscape during streamflow drought can be created.

MOTIVATION

From the beginning of my studies, I have been interested in climate adaptation. My projects incorporated different types of climate-related problems over the years. During my bachelor's, I did a minor in climate adaptation. But the one subject I had not done a project about was drought, as in my eyes, this was not a big problem in Europe. This changed when I visited the city of Arnhem in the summer of 22, where I saw the river's low water levels. From that point on, I started to pay more attention to news articles, and it became apparent that drought was a severe problem that we don't hear much about.

During my studies, I have gained a lot of knowledge on the subject of climate adaptation, but I wanted to extend that knowledge further with a project about drought. This started my search for a project location that I wanted to do. While exploring different options and countries, I eventually landed on the Rhine. With this location, I would also be doing a large-scale project outside of the Netherlands for the first time. This was an extra reason to do this project on drought along the Rhine.

This thesis turned into a project where I learned much more than just about drought. With the scale I chose, I also needed to look at different ways to analyse and process data. I had not thought about this beforehand, but it kept me motivated to explore even further.

GLOSSARY

Absorption – The process of water taken up by plants from the soil and released back into the atmosphere.
Aquifer – An underground of porous rock, soil, or sand. It contains water that moves through the porous layer.
Fissured aquifer – Aquifers composed of rocks with fractures or cracks, allowing water to flow through them. These aquifers typically lay deep in the earth's surface.
Geology – Study of the earth's physical structure and the processes that shaped it.
Geomorphology – The study of the surface landforms of the earth and the processes that shaped them.
Groundwater recharge – The process of absorbing precipitation into the ground and replenishing aquifers.
Infiltration – Described by R. Horton as *'limited to water in the liquid form and is more accurately descriptive of the physical process by which rain enters the soil'* Horton (1933).
Patterns – Design principles that explain the implementation and function, categorized into different aspects of the built environment.
Percolation – Described by R. Horton as *'the free downward flow by gravity of water in the zone of aeration'* (Horton, 1933).
Porous aquifer – Aquifers composed of permeable rock or sediment, allowing water to flow through the porous spaces. Typically these aquifers are shallow.
Precipitation – Any form of water that falls from the atmosphere. This includes rain, snow and hail.
River landscape – Stanford et al. (2017) describes river landscape as *'an expansive view of a stream or river and its catchment, including natural and cultural attributes and interactions'* (riverscape).
Rural and urban – Rural area is covered mainly by agricultural land, forest and natural areas, including disadvantaged areas for human activities like mountains and extreme climate conditions. Urban are those areas that have been used for human activity, areas that do not fit under the description of rural.
SPEI – Standardised Precipitation-Evapotranspiration Index.
SPI – Standardized Precipitation Index.
Streamflow – The amount of water flowing in a river or stream.
Topography – The study of the shapes and structures of the earth's surface.
Water demand – Described by Takeuchi (1974, p. 4) as '*that amount of water necessary for satisfying man's activities, which includes water not only for man's physical and economic needs but also for the environmental, ecological and cultural needs which have benefits to man but not necessarily measured as tangible benefits'*.

CONTENT

INTRODUCTION

1.

Figure 1: The romantic Rhine. A. Lasinsky 1808 - 1871 & Hammerstein 1835 (Rhein-Museum Koblenz)

1.1 DROUGHT

Definition

It is first of all important to define drought at the start of this thesis. To accomplish this, several drought definitions will be explored and finally used to state a definition for drought to be used in this thesis.

Tate and Gustard (2000, p. 23) indicate that drought can be either described with qualitative (usually descriptive, linguistic definitions of drought severity) or quantitative (requiring the use of statistical analysis) indicators. For this thesis, a qualitative indicator would be more helpful as this thesis is not a measurement of drought but is about using drought indicators for design.

Dracup et al. (1980) consider drought events to be composed of duration, magnitude (average water deficiency), and severity (cumulative water deficiency). They explain that the problem with the definition of drought is the conflicting concepts used by different academics. Hydrologists, meteorologists, agriculturalists and economists have different ideas of drought. But these concepts will also vary among regions with different climates. For this research a definition that urbanists can use will be explored.
Dracup et al. state that to define the type of drought event to be studied, a set of decisions must be followed. The set described by Dracup et al. is as follows:
'(1) Is the primary interest in precipitation (meteorologic drought), streamflow (hydrologic drought), or soil moisture (agricultural drought)?
(2) What is the fundamental averaging period of the time series to be studied (e.g., month, season, or year)?
(3) How are drought events distinguished analytically from other events in the time series?
(4) How are the regional aspects of droughts to be considered in the study?'

When looking at the water cycle, it is clear that low precipitation, low run-off, and low soil moisture are related. Precipitation is an input, and streamflow is an output. Dracup et al. (1980) specify that when one is interested in determining the cause of drought events, one should pay attention to precipitation drought. Still, when one is interested in determining the effects and impacts of drought events, one should also pay attention to streamflow drought and agricultural drought.
This research will examine the effect and impact of drought along a river landscape, focusing on streamflow drought. With this, the first decision in the set of decisions by Dracup et al. has been made.

On to the following two steps in the set of decisions: the time series to be studied and distinguishing drought events from other events.
Tate and Gustard (2000, p. 38) describe a month as the usual timeframe for river flow drought studies. '*As a time unit, the month is long enough to eliminate all less significant, extreme events, and is short enough to allow the monitoring of drought effects in agriculture, water supply and groundwater levels.*' For this thesis, the time frame is less important because it is working towards a design proposal. But with the statement of Tate and Gustard, it can be assumed that a timeframe of at least a month will be needed to distinguish drought events from other events. Since this thesis does not look into the monitoring of agriculture, water supply or groundwater levels, a timeframe longer than a month would also be applicable to this research.

The last decision in the set is the regional aspects of drought. This would be the no-regionalisation option, as used by Dracup et al. (1980). With this, the analysis will not be regionalised. The attention of drought will only focus on one stream gauge, rain gauge, or moisture gauge. For drought measurements, this option is not feasible. But since this thesis focuses on design aspects around a single river, the no-regionalisation strategy will be the most applicable.

Answering the questions of Dracup et al. (1980), this research focuses on streamflow drought in a time set of at least a month, with a no-regionalisation strategy.

Some definitions of drought could be a good fit for streamflow drought around the Rhine for design research. Beran et al. (1985, p. 2) use this definition: '*The chief characteristic of a drought is a decrease of water availability in a particular period and over a particular area.*' Ben-Zvi (1987, p. 179) defines drought as '*a severe shortage in natural waters with respect to normal for place and time*'. Both of these definitions look at the shortage or decrease of water during an unspecified timeframe, whereas the definition of Ben-Zvi has a comparable aspect of what would be the normal circumstances for the streamflow.

Takeuchi (1974) states that '*whenever the amount of water which has been expected and relied upon for use in any of man's activities cannot be met for reason, a drought condition is established*'.
With this definition, human activities are brought into the definition of drought. This can be of use for the main aim of this thesis, to keep the Rhine vibrant and functional.

The definition set by the World Meteorological Organization (2006) is '*an insidious natural hazard characterised by lower than expected or lower than normal precipitation that, when extended over a season or longer period of time, is insufficient to meet the demands of human activities and the environment*' can also be used. Here human activities and normal circumstances are both combined and give a well-rounded definition. The definition of the World Meteorological Organization will be the base for this research.

Types of drought

Drought is a phenomenon that exists in different phases. Therefore it is important to explain these differences in drought for this thesis. The different types of drought are portrayed in figure 1.1.

A lack of precipitation, in combination with high evaporation rates, causes drought. The changes in weather patterns can result from the variation in climate. When periods of greater sunshine, less cloud cover, low relative humidity, higher temperatures and precipitation deficiency occur, drought is likely to occur. We talk about climate variability when these changes occur over more extended periods than just weather changes. Or as University Corporation for Atmospheric Research (n.d.) (UCAR) describes it, '*when aspects of climate differ from an average. Climate variability occurs due to natural and sometimes periodic changes in the circulation of the air and ocean, volcanic eruptions, and other factors*' (University Corporation for Atmospheric Research, n.d.).
These more prolonged periods of a warm, dry climate can lead to drought. Because of the timeframe drought takes to set in, the lack of water can be severe, and when it finally rains, it can take months for streamflows, aquifers, groundwater and soil moisture to recover (Water Science School, 2018).

There are two main drought events that have different causes and impacts on the environment and human activities. 'Summer droughts' are caused by a combination of lack of precipitation and high evaporation rates, as described above. 'Winter droughts' result from a lack of precipitation or this precipitation being stored as snow. This research looks into the impacts 'summer droughts' have on the functions of the Rhine. During the summer, more functions are under pressure during drought, and these droughts are more common in Europe (Hisdal et al., 2001).

This research looks into the four types of drought: meteorological, agricultural, hydrological, and socioeconomic.
Meteorological drought occurs when there are prolonged periods of below-average precipitation. These events are caused by changes in weather patterns and lead to a lack in soil water infiltration, groundwater recharge and run-off. When these periods of below-average precipitation persist, the next phase of drought happens.
Agricultural drought is the lack of soil moisture and affects crop production and the food supply.
The next phase is hydrological drought. This phase is reached when streamflows, lakes and groundwater see a significant water reduction. Hydrological drought significantly impacts human activities, agriculture, industry and wildlife habitats.
The last type of drought is socioeconomic drought. This can occur during the different phases of drought and is defined as when the lack of water affects the economy and well-being of people (Chamorro et al., 2020).

This research focuses mainly on the impact of hydrological and socioeconomic drought on functions in and around the Rhine. When the Rhine experiences hydrological drought, the effect of drought is severe, and agriculture, flora and fauna, economic sectors and human activities are all affected. The impact of these consequences on the functions of the Rhine will be the main focus of this research.

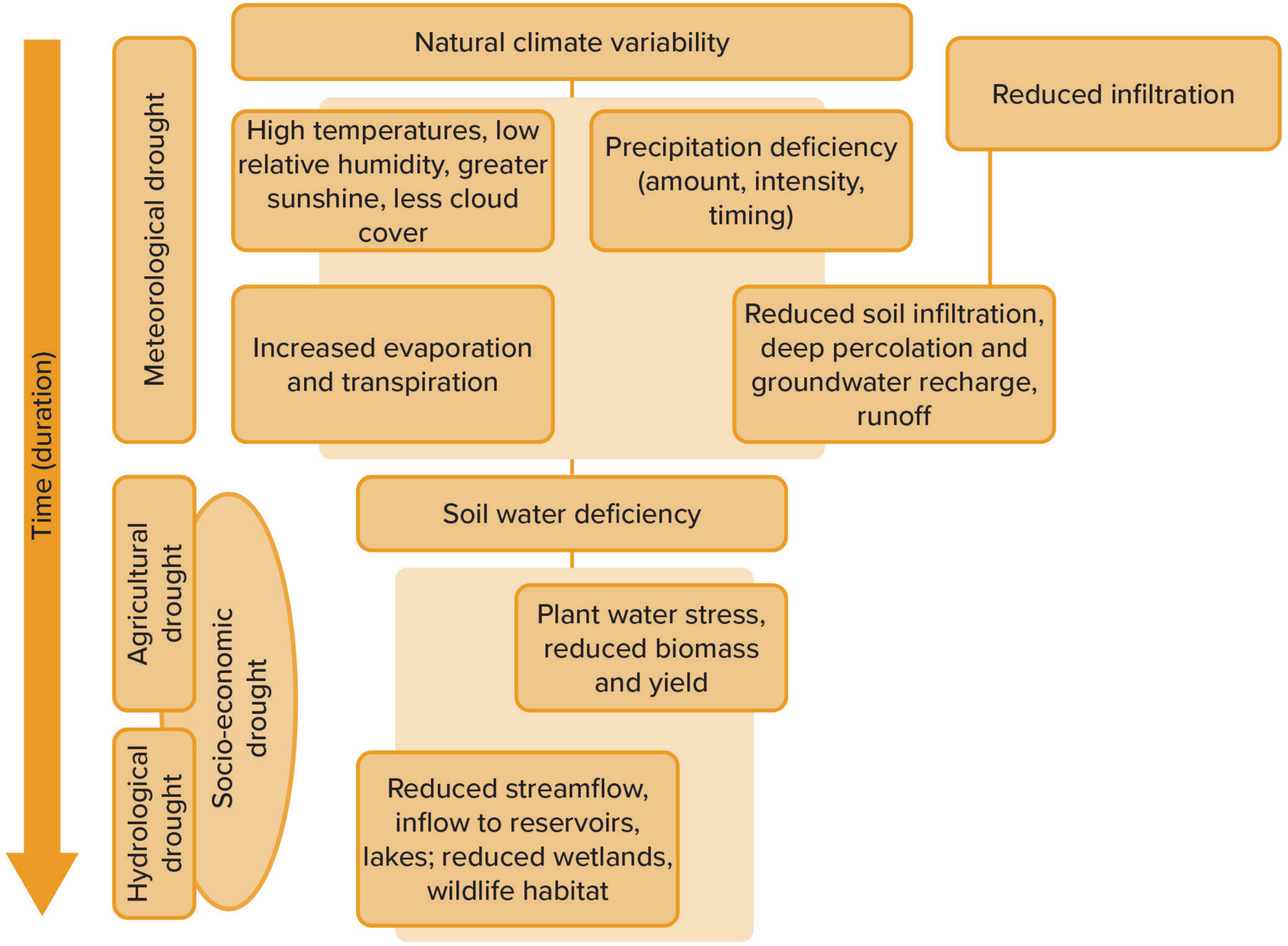


Figure 1.1: Types of drought. Made by Author, based on World Meteorological Organization (2006)

Indicating drought

There are many different ways to measure drought. This section gives a short overview of the types of indications. This research does not aim to measure drought but will use various sources that use drought measurements.

The Standardised Precipitation Index (SPI) is a widely used indicator of drought. The index is based on the precipitation accumulated over a specific period. Other natural processes that impact the water balance are not accounted for in SPI. SPI's most commonly used time frames are 1, 3, 6, 9, or 12 months.

A variant of the SPI is the Standardised Precipitation-Evapotranspiration Index (SPEI). SPEI takes evapotranspiration into account as well as precipitation. The index takes into account that water is not evenly divided throughout the year. It has the same time frames as SPI.

The Palmer Drought Severity Index (PDSI) is another widely used indicator of drought. This index uses a water balance model to consider the available water in the soil and the evaporation rates. PDSI is based on meteorological and geological data.

Soil Moisture Index (SMI) is commonly used during agricultural drought. This indicator measures the amount of moisture in the soil. Satellite data or ground-based sensors collect the data used for this index.

The choice of drought indicator depends on the context and purpose of the research. For Europe, the SPI performs well enough and is often used in research. Since periods of drought have become more common, SPEI has been used more often as this gives a more specific indication of drought. The PSDI is less common in Europe as this is a very complex indicator (Chamorro et al., 2020; Koninklijk Nederlands Meteorologisch Instituut, n.d.-a).

Rivers and drought

Drought significantly impacts rivers, altering flow patterns and causing severe ecological consequences to the surroundings. Lack of precipitation affects the river inflows, mostly from rainfall and groundwater. During drought, rivers can experience low flow and even completely dry up in extreme cases. Drought disrupts the natural balance of the water cycle. The reduced river flows cause less water to be transported to the oceans, impacting the freshwater-saltwater balance. The reduced flow can lead to ecological consequences for ecosystems that rely on the influx of freshwater. Moreover, low river flows can lead to salt intrusion, compromising water quality.
So drought in rivers causes problems for functions that rely on the water supply of rivers and can affect both humans, the economy and ecosystems.

Rivers are a primary water source, and the dependency on rivers becomes even more apparent during precipitation scarcity. Rivers can act as buffers to mitigate the economic impacts and food scarcity caused by drought. When the buffers run dry, there is insufficient water for the irrigation of crops, water supply for urban areas diminishes and can impact the drinking water supply. Manufacturing processes that rely on river water are reduced during low river flows and can affect production and potentially shut down businesses (United States Environmental Protection Agency, 2022).

Droughts in rivers have a significant impact on the ecosystems surrounding these rivers. Evaporation rates affect the moisture levels in vegetation zones, and combined with low river flows, vegetation sees a significant reduction in water availability, causing damage to the plants and species that exist here. Aquatic systems see a degradation in the habitats caused by low flows. Aquatic organisms face limited access to suitable habitats, and fish populations struggle to migrate or even experience a lack of air in the water. Simultaneously with lower water levels, rivers heat up more excessively, causing an uninhabitable environment for some species. Droughts in rivers disrupt the balance of ecosystems and further exacerbate the impact of drought on ecosystems.

Even though rivers are affected by drought, they can serve a mitigating role in the effects of drought during dry periods. Rivers act as natural water storage systems, accumulating water during wet periods and releasing this during dry periods. When correctly managed, rivers can provide this buffer against the impacts of drought, ensure a more consistent water supply, and provide essential needs such as drinking water supply and irrigation for agriculture.

1.2 PROBLEM FIELD

1.2.1 THE NEWS

Throughout the year of working on this thesis, headlines from news articles were collected about drought, specifically drought along the Rhine. In this short period, the problems affecting the functions around the Rhine become apparent, and predictions for the future are displayed. Overall the articles around this topic show a very gloomy view of the effects of drought on the Rhine and its surroundings, now and in the future.

Niedrigwasser

Bundesamt: Regen wird Rhein nicht viel helfen

Figure 1.2: Federal Office: Rain will not help the Rhine much (ZDFheute, 2022)

Why Scientists are using the word scary over the climate crisis

The former BBC environment analyst Roger Harrabin has spent his career talking to scientist. Now they're telling him they're scared of what they're seeing

Figure 1.3: (Harrabin, 2022)

De Rijn is te droog voor binnenvaart, die juist cruciaal is voor de Duitse economie

Figure 1.9: The Rhine is too dry for inland navigation, which is crucial for the German economy (Bekkum, 2022)

Waterpeil in de Rijn keldert, Nederland moet zich opmaken voor extreme droogte

Figure 1.10: Water level in the Rhine plummets, the Netherlands must prepare for extreme drought (Brandsma, 2022)

Waterpeil in de Rijn zakt tot 'kritiek niveau' door extreme droogte

Figure 1.11: Water level in the Rhine drops to 'critical level' due to extreme drought (Brandsma, 2022)

Rette sich, werr kann - Wie Deutschland sich für die Klimakrise wappnet

Figure 1.4: Save yourself if you can - How Germany is arming itself for the climate crisis (Duhm et al., 2022)

De Rijn: 220 dagen met lage waterafvoer in 2022

Figure 1.7: The Rhine: 220 days with low water discharge in 2022 (H2O Waternetwerk, 2023)

De winterdroogte die grote delen van Europa nu treft, zal in de toekomst vaker voorkomen

Watertekort Droogte in de winter speelt Europa parten. Het mediterraan gebied is "een van de hotspots van klimaatverandering".

Figure 1.5: The winter drought that is now affecting large parts of Europe will become more frequent in the future (Burgh, 2023)

Amper regen en hoge temperaturen: hoe Europa uitdroogt

Klimaat Europa droogt uit. Een gebrek aan neerslag en grote verdamping zorgen voor watertekorten. Wat is er aan de hand?

Figure 1.6: Hardly any rain and high temperatures: how Europe is drying out. Climate. Europe is drying up. A lack of precipitation and large evaporation cause water shortages. What is going on? (Poort & Gameren, 2022)

Amper is het voorjaar begonnen of een groot deel van Europa is al uitgedroogd

Klimaat Vooral in Zuid-Europa is het al vroeg in het jaar extreem droog. Onderzoekers waarschuwen dat Europa beter zal moeten nadeken over de verdeling van het beschikbare water.

Figure 1.12: Barely has spring started or a large part of Europe has already dried out (Luttikhuis, 2023)

Niet eerder sinds begin metingen zoveel ijsverlies in de Alpen

Figure 1.13: Not before since the beginning of measurements so much ice loss in the Alps (Kersten & Ekker, 2023)

Bauern bekommen Klimawandel deutlich zu spüren

Figure 1.15: Farmers are clearly feeling the effects of climate change (Marquart, 2022)

Gletsjers smelten sneller dan verwacht: zelfs in beste scenario verdwijnt helft deze eeuw

Figure 1.8: Glaciers melt faster than expected: even in best-case scenario half will disappear this century (NOS Nieuws, 2023)

Dürre-sommer 2022

"Vater Rhein" verlässt sein Bett: Deutschlands längster Strom fällt trocken

Figure 1.14: "Father Rhine" leaves his bed: Germany's longest river falls dry (Stern, 2022)

1.2.2 CAUSES

As described before in section 1.1, there are different types of drought. World Meteorological Organization (2006) defines drought as '*an insidious natural hazard characterised by lower than expected or lower than normal precipitation that, when extended over a season or longer period of time, is insufficient to meet the demands of human activities and the environment*'. The lack of precipitation is part of what is known as climate variability. The natural differences in climate between years causes periods to have an extreme lack of precipitation. In figure 1.31, types of drought are marked with yellow. Climate variability is the difference in climate, so due to climate variability, we can experience a combination of high temperatures, low relative humidity, greater sunshine and less cloud cover. Together with precipitation deficiency, this can lead to increased evaporation and transpiration. Reduced infiltration causes groundwater depletion. These are the first stages of drought, the meteorological drought. When these weather conditions stay over time, a soil water deficiency will occur, the agricultural drought. Finally, we experience reduced streamflow and have reached a hydrological drought. Recovery from a hydrological drought takes a long time, as some precipitation won't help much and groundwater levels need to recover simultaneously.

Precipitation is a significant input for the streamflow of the Rhine. During summer, the streamflow partly depends on meltwater from snow and glaciers. During autumn and winter, the streamflow gets its water primarily from rainfall. Stahl et al. (2022) modelled the streamflow for 1901-2006, showing that snowmelt has been a considerable streamflow component year-round. The glacier melt feeds the streamflow of the Alpine tributaries. Even though glaciers are retreating, the lack of meltwater from glaciers is supplemented by snowmelt. During extreme low-flow situations, one-fifth of the inflow to the Rhine can be assigned to ice meltwater (Stahl et al., 2022).

Figure 1.16: Low water levels near Emmerich. (Offern, 2022)

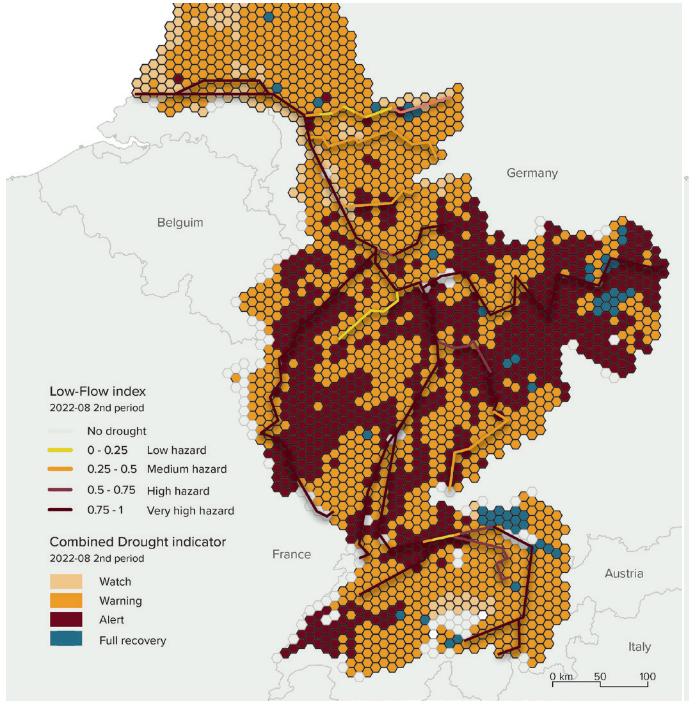


Figure 1.17 Based on European Drought Observatory (2023). Altered by Author

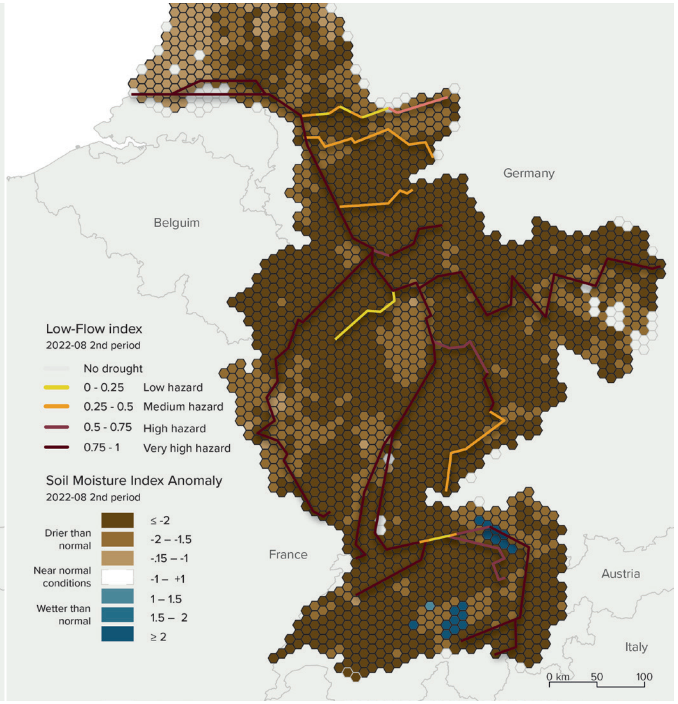


Figure 1.18 Based on European Drought Observatory (2023). Altered by Author

The combined drought indicator (figure 1.17) expresses the consequences of drought. It comprises the Standardised Precipitation Index (SPI), Soil Moisture Anomaly (SMA) and fraction of Absorbed Photosynthetically Active Radiation (fAPAR). This indicator shows the areas with potential for agricultural drought. The map is of August 2022 and shows large areas with agricultural drought and areas where plants are affected by drought. The soil moisture index anomaly (figure 1.18) shows that nearly all parts of the Rhine catchment area had drier than normal soil in August 2022. This drought had a significant impact on the streamflow of the Rhine. The low-flow index (figures 1.17 & 1.18) shows the hazard the streamflow has for flow reduction. The Rhine had a very high hazard at this stage, as did most tributaries. All tributaries were affected by the drought during this drought event. Near Kaub, the lowest water level point of the Rhine, water levels almost reached 30 cm. When water levels reach this number, inland water transport on the Rhine is no longer possible.

The Rhine is one of Europe's largest rivers, accounting for two-thirds of all inland waterway transports across Europe (Trouw, 2022). The Rhine is essential for transporting goods, power production, fresh water supply, industry, and other water uses. During the autumn and winter, precipitation is the most crucial supplier for the streamflow of the Rhine. In springtime, snow- and glacier meltwater are significant feeds for the streamflow (Stahl et al., 2022). Drought significantly impacts the amount of precipitation, and changes in drought increase when precipitation diminishes. A lack of water substantially affects the surrounding functions of the Rhine. Even though the impacts of drought are already noticeable, because drought is a slow-onset natural hazard, its consequences are often forgotten. There is not as much prevention for drought as there is for flooding. Drought has fewer immediate consequences, and investment in prevention has not been a top priority. After the drought periods in 2018 and 2022, drought has made a big impact and is now slowly being taken into account.

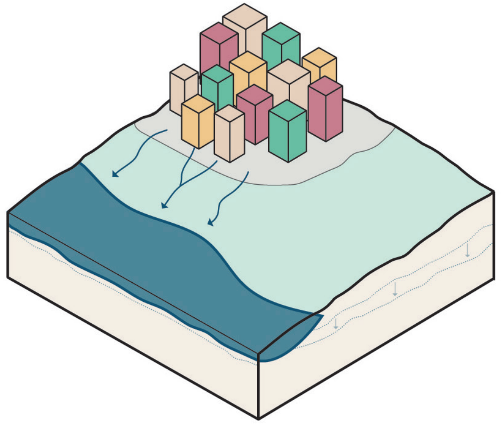


Figure 1.19: Run-off, made by Author

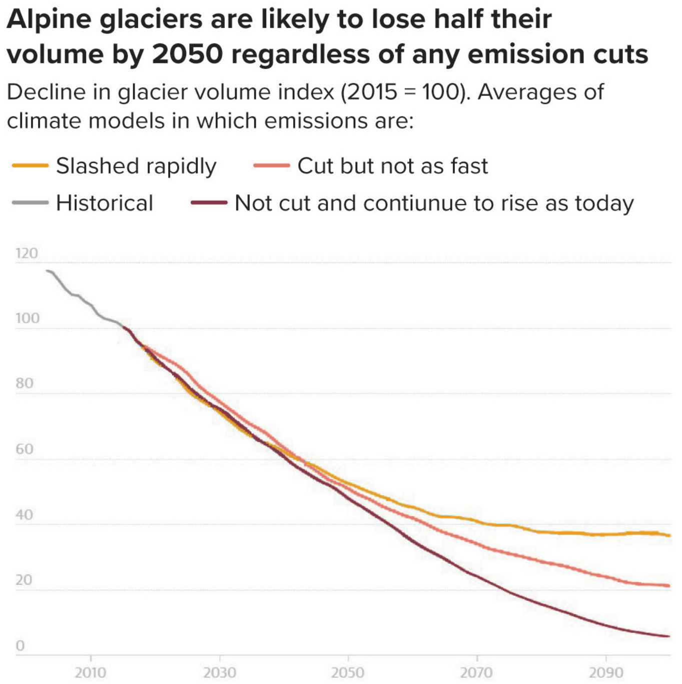
Figure 1.20: Water level difference of the Rhine (Offern, 2022)

The expanding built environment is also responsible for drought by causing a reduction in infiltration, causing more run-off where water will be taken away as fast as possible. There is no time for infiltration into the soil (see figure 1.19). During periods of heavy rainfall, water will be guided away as fast as possible, but this has the opposite effect on drought. Groundwater cannot recharge, and there will be soil water deficiency. Low groundwater levels lead to plant water stress, noticeable in agriculture and cities, as greenery will decline. The effects in agricultural sectors around the world are already apparent. The wine industry along the Rhine has been significantly affected due to drought. And with streamflow reduction, last-resort irrigation with the Rhine as a source is no longer possible.

1.2.3 THREATS

While Europe is already dealing with drought more and more, climate change will, in the long run, cause even more considerable differences in the weather pattern. The World Weather Attribution (2018) presents in a study '*that the probability to have such a heat or higher is generally more than two times higher today than if human activities had not altered climate'.* Due to climate change, drought occurrences might double. In figure 1.23, the precipitation deficiency with prospects for the future in the summer half-year for the Netherlands is visible. It is noticeable that the precipitation deficiency will increase in most scenarios. The Standardised Precipitation Evapotranspiration Index (SPEI) (figure 1.22) also shows noticeably worse drought scenarios in the summer half-year for the Netherlands. Assuming that there will also be a noticeable declining trend in precipitation deficiency for Germany, the Rhine is likely to experience more severe periods of drought.

As stated before, glaciers are retreating and will eventually disappear. Even in the best-case scenario, the glaciers will disappear by 49% by 2100. Still, with current rates, it is more likely that 68% of the glaciers will have already disappeared by that time (figure 1.21). Central Europe, the United States, West Canada, and New Zealand will have almost no glaciers anymore (NOS Nieuws, 2023). No more glaciers also mean that they will not feed the streamflow of the Rhine anymore. Dr. Klaus Lanz of the research institute International Water Affairs states in an article that by 2100 the meltwater of glaciers will contribute less than 1% to the streamflow of the Rhine (Niet, 2021). At the same time, the increasing temperature will also impact the snowfall. The fluctuation of the water levels of the Rhine will shift drastically and become less predictable. With flooding, we could quite possibly experience large water quantities in the winter, disrupting inland waterway transport. Drought could be much more frequent in summer, making transporting large amounts of product impossible. This unpredictability makes for an unsure future (M. Huss & GLAMOS, 2018).



Source: Carrington, 2019

Figure 1.21

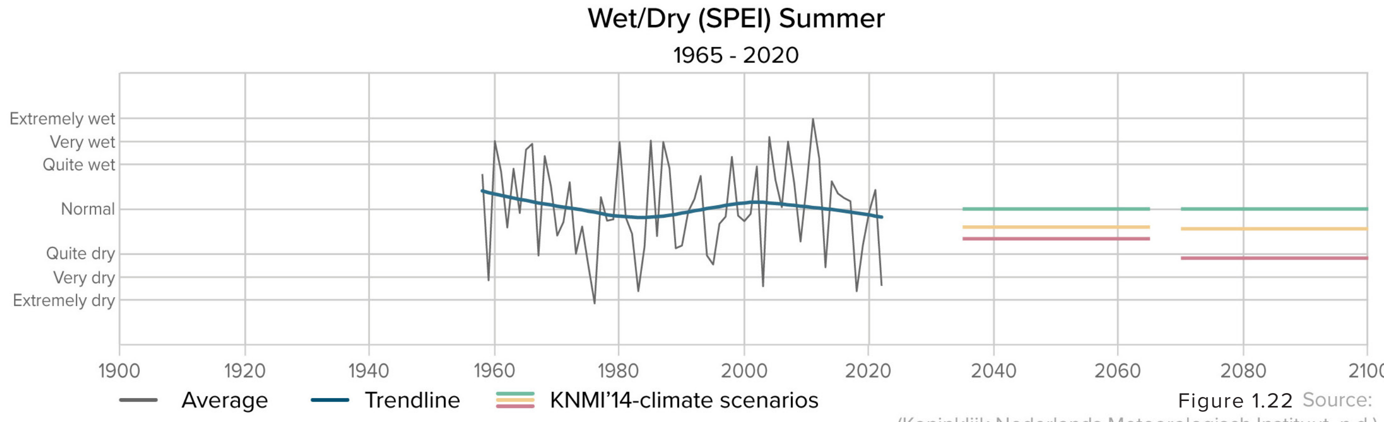


Figure 1.22 Source: (Koninklijk Nederlands Meteorologisch Instituut, n.d.)

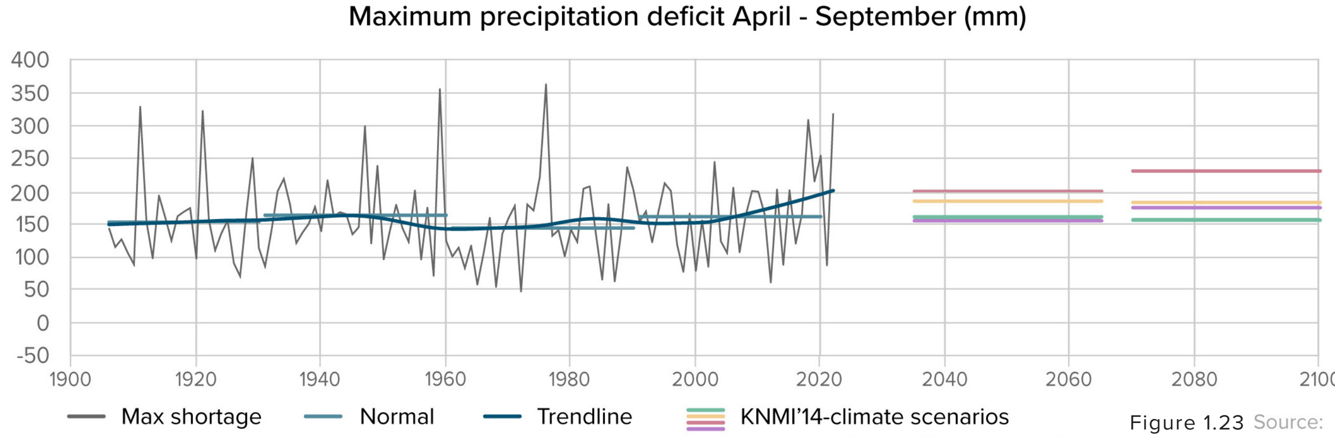


Figure 1.23 Source: (Koninklijk Nederlands Meteorologisch Instituut, n.d.)

Figure 1.24: Glaciers melting between 2006 and 2018 (Huss & GLAMOS, 2018)

The catchment of the Rhine is not known for its wildfires. But with the climate changing, the risk of wildfires is increasing (see figure 1.26). The climate is getting hotter, drier and sunnier, and it is predicted to continue to increase. This climate and the other circumstances touched upon earlier can lead to soil water deficiency. The soil water deficiency will cause plant water stress, increasing the flammability of vegetation. Europe will be confronted with more wildfires, and the consequences have already been visible in the past few years. These fires will impact people living near vulnerable areas, industries located there, recreative purposes of nature, and vital infrastructures. Besides that, ecosystems are under pressure because wildfires and droughts occur more often. When ecosystems have no time to recuperate between events, permanent damage will occur. (Copernicus, 2021; European Environment Agency, 2021; Verhoeven et al., 2023)

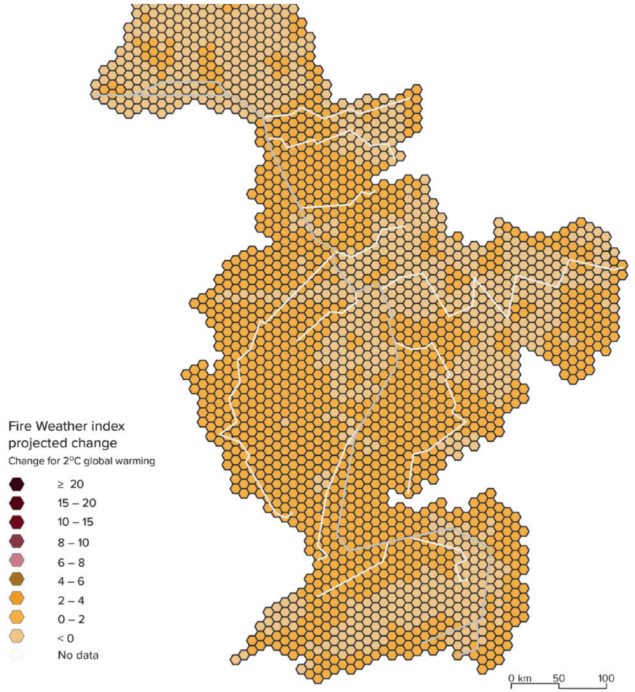


Figure 1.25: Fire Weather index. Based on Esri (2021b). Altered by Author

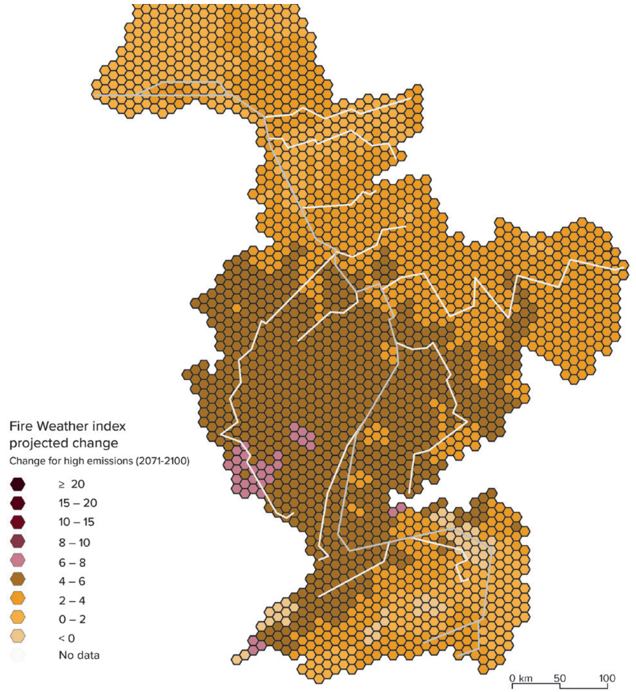


Figure 1.26: Fire Weather index. Based on Esri (2021b). Altered by Author

Figure 1.27 shows that the urban population has grown in the past decades. This led to the growth of cities, which has increased the amount of impermeable surfaces. These impermeable surfaces leave less room for infiltration. These trends will likely continue for the next decade. Figure 1.28 shows the land cover vulnerability to change in 2050. Green spaces have a high chance of getting converted into arable land, industry or built environment. The conversion of green spaces also leaves less room for infiltration on the surface. The pressure on freshwater also expands rapidly with the growth in agriculture and industry. Large parts of the Rhine's catchment area depend on the Rhine for their freshwater supply. With increasing pressure and declining water levels, this could become more problematic in the future, and the functions along and on the Rhine are under pressure.

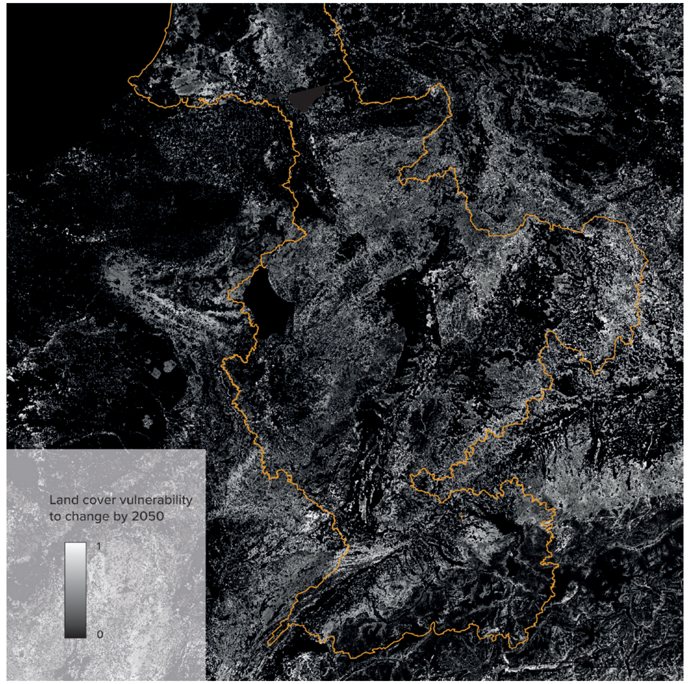


Figure 1.28: Land cover vulnerability to change by 2050 (Esri, 2021)

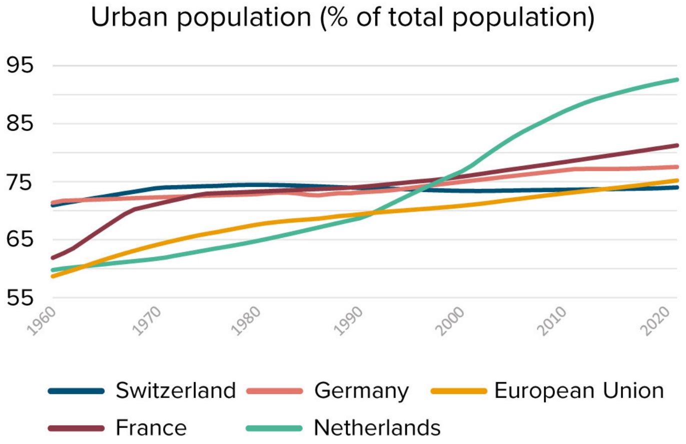


Figure 1.27: Based on United Nations Population Division (2018 Revision). Alterd by Author

Drought is a slow-onset natural hazard, meaning the problems it causes are hardly noticeable initially. The consequences of drought are mostly indirect (figure 1.30), while flood-related consequences would be most direct. When the stage of immediate consequences has been reached, the damage will be primarily irreversible and recovery from drought has a lengthy recovery period. Because of the direct effects of a flood, action is taken preventively as damage is more visible, leaving areas more prepared for flood events than drought events.

Figure 1.29: Subsidence due to dry summers (BNNVARA, 2019)

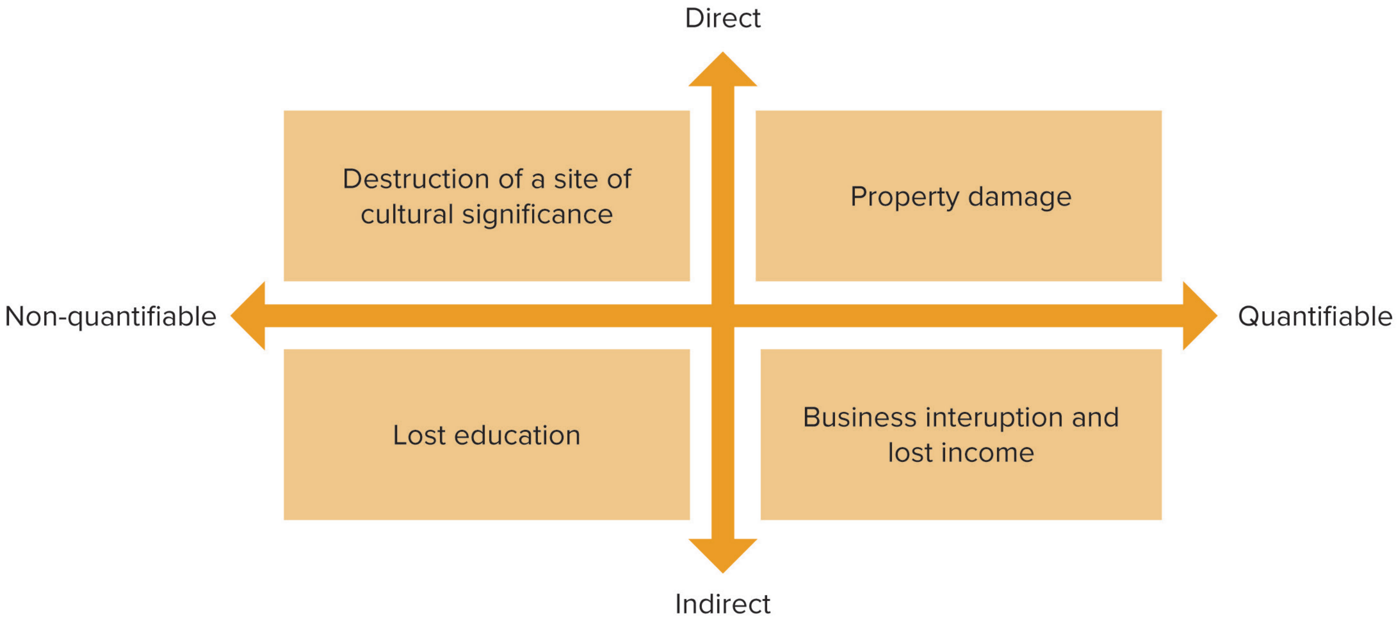


Figure 1.30: Indirect and intangible losses. Based on PreventionWeb (n.d.)

1.2.4 SUMMARY OF PROBLEMS

We now see different problems occurring along the Rhine due to drought:

- The Rhine experiences more low flow. In 2022 there were 220 days with low water levels (H2O Waternetwerk, 2023).
- There is a shortage of drinking water, an irrigation ban for surface and groundwater use, and a need for responsible use during extreme periods (Ons water, 2022).
- Ships can only take small portions of their payload because of low water levels. This had significant economic consequences for all of Europe. Two-thirds of all inland waterway transport in Europe goes across the Rhine. (NOS Nieuws, 2022)
- In 2022 Germany was very dependent on coal due to the war in Ukraine. Due to the low water levels of the Rhine, coal could not be supplied, leading to production problems in some power plants. (Waterval, 2022)
- Functions of the Rhine are under pressure. Due to changes in weather patterns, worsened by climate change and glaciers melting, water levels will fluctuate more in the future, making it harder to predict water levels. This can lead to economic consequences and problems with energy production, agriculture, industry and inland waterway transport.
- With air temperatures rising, the water temperature also increases. With lower water levels, the water heats up easier than under normal circumstances. Many industries use Rhine water as cooling water, putting warmer water back into the river. Due to these functions, water temperatures rising, and already battling with salinisation, water pollution has more chance to set in. Algae have a better opportunity to grow in these circumstances, affecting the drinking water supply.
- Lower water levels allow subsidence, significantly affecting building structures near the Rhine. These structures can subside and cause structural problems.

1.2.5 PROBLEM STATEMENT

Low water levels can have severe consequences for ecosystems. When drought events occur year after year, ecosystems come under pressure as they have no time to recover and get permanently damaged.
During the summer half-year, drought has become a more apparent problem. Natural climate variability causes some summers to have more drought periods than others. Due to this, the streamflow of the Rhine can become dangerously low. This has a significant impact on many functions and ecosystems that are dependent on this streamflow. Since the Rhine accounts for two-thirds of all inland waterway transports across Europe (Trouw, 2022), Europe experiences economic consequences when the streamflow gets low. Goods can no longer be shipped. Industries and agriculture along the Rhine also depend on this water supply. More importantly, the Rhine also serves as a source of clean drinking water. During droughts, these functions become under pressure.

With growing urbanisation, industries and agriculture along the Rhine, the pressure on the water supply grows. The chances of more periods of drought are also increasing. Due to climate change, the source of the Rhine slowly moves from glacier and snow meltwater to entirely rainwater based. Rainwater-based streamflow causes water levels to fluctuate more throughout the year, and dry summers can become up to two times more likely. The functions of and on the Rhine are threatened due to drought, which will only increase in the coming decades. Problems like salinisation, water pollution, shortage of drinking water, subsidence, damage to ecosystems and rising water temperatures will only become more apparent in the future.

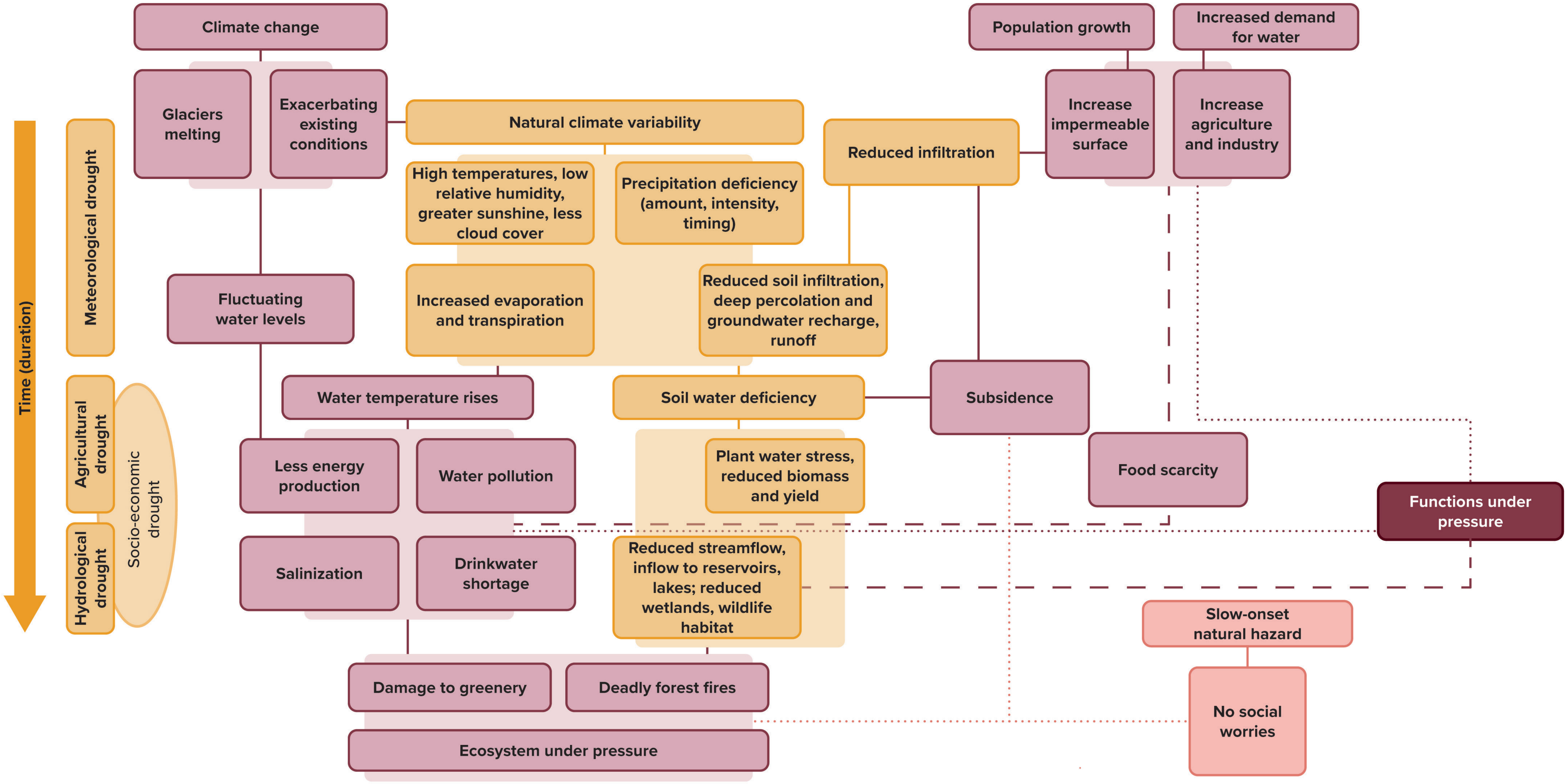


Figure 1.31: Visual summary of the problem statement. Made by Author

1.3 GOALS AND AIMS

The project's goal is to show how the surrounding landscape of the Rhine River can contribute to mitigating drought-related problems and keep the riverscape functional.

This project aims to create a resilient river landscape during streamflow drought. The aim is to accomplish this by creating a synergy between urban and rural river landscapes that apply drought-mitigating measures to combat the impact of drought along the Rhine. A green-blue infrastructure approach will be implemented along the Rhine to achieve this synergy. This infrastructure will be supported by nature-based solutions that aim to reduce drought problems. These supporting nature-based solutions will be translated into a drought-mitigating pattern catalogue focusing on creating this green-blue infrastructure.
A vision will be created to display how the green-blue infrastructure will function along the Rhine and how the different design scales intertwine and create one design strategy. The current water system and river landscape will be mapped to accomplish this. This will then lead to problem and opportunity maps. These maps allow the potentials along the Rhine to be identified and used as input for a design location. These design locations will then be used to test the drought-mitigating pattern catalogue.

Low water levels during streamflow drought can severely impact functions around the Rhine. This project aims to improve living-, economic-, and recreational conditions during periods of drought. Improving these conditions is essential to lessen the impact of drought on society by creating a design strategy that will revolve around a drought-mitigating riverscape.

Drought in relation to climate adaptation has not yet been as explored as other climate adaptation strategies, especially in Europe. An attempt to close this gap, and ensure that climate adaptation strategies will be implemented for drought, will be made with this research. Creating a new drought-mitigating pattern catalogue will address the gap in the knowledge of urbanism and drought as climate adaptation strategies.

SUSTAINABLE DEVELOPMENT GOALS

At the heart of the 2030 Agenda for Sustainable Development lay the 17 Sustainable Development Goals (SDGs). These Goals share a way towards peace and prosperity for people and the planet. These SDGS are an urgent call for action, adopted by all United Nations Member States in 2015(United Nations, 2022a). For Every Drop Count, four goals are selected and described that are specifically applicable to the research.

'As the world faces cascading and interlinked global crises and conflicts, the aspirations set out in the 2030 Agenda for Sustainable Development are in jeopardy. With the COVID-19 pandemic in its third year, the war in Ukraine is exacerbating food, energy, humanitarian and refugee crises – all against the background of a full-fledged climate emergency' (United Nations, 2022b).

Clean water and sanitation

Ensure availability and sustainable management of water and sanitation for all.

Safely managed drinking water, sanitation, and hygiene are vital to human health. Clean water demand is rising. Population growth, urbanisation, and added pressure from agriculture, industry and the energy sector increase the demand. Mismanagement, over-extraction and contamination of water supplies intensify water stress and harm ecosystems.

Sustainable cities and communities

Make cities and human settlements inclusive, safe, resilient and sustainable.

Well-planned sustainable urban development is necessary to reduce greenhouse gasses produced by cities. Poorly planned urbanisation increases inequalities. Adopting disaster risk reduction strategies is essential for the cities vulnerable to these.

Climate action

Take urgent action to combat climate change and its impacts.

The world is close to a climate disaster. There is an increase in heatwaves, droughts and floods caused by climate change. Countries develop climate action plans and adapt to climate impacts. But current plans are insufficient to reach the 1.5 °C target from the Paris Agreement. And we are heading to the tipping point of climate calamity.

Life on land

Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss.

Human activity has altered most of the terrestrial ecosystems but is working to halt the degradation of ecosystems. It is necessary to create healthy ecosystems to help clean water, as water sustains life. A healthy ecosystem will be more resilient when disaster strikes.

Source: United Nations (2022b)

1.4 RESEARCH QUESTIONS

How can the river Rhine stay a functional riverscape by creating a synergy between urban and rural areas while using the green-blue infrastructure approach to mitigate drought-related problems?

Analyses

To understand the environmental impact of drought on functions of the Rhine.

How does streamflow drought impact the Rhine and the surrounding landscapes?

To understand the social impact of drought on functions of the Rhine.

How are the functions of and on the Rhine affected by drought?

To find solutions to combat the impact of drought on functions of the Rhine

Vision

How can the green-blue infrastructure approach be used to form a synergy between urban and rural river landscapes?

Strategy

How can nature-based solutions be used for drought-mitigating strategies along the Rhine?

Design

How can the desired drought-mitigating strategies be implemented along the Rhine?

Figure 1.32: Burg Gutenfels, Kaub (Author, 2022)

1.5 CONCEPTUAL FRAMEWORK

World Meteorological Organization (2006) defines drought as '*an insidious natural hazard characterised by lower than expected or lower than normal precipitation that, when extended over a season or longer period of time, is insufficient to meet the demands of human activities and the environment*'. The variability in climate is what is the main instigator of drought occurrences. Natural differences in climate occur between different years, causing some years to have periods of drought. Climate variability is a natural occurrence. But climate change is exacerbating the probability of an extreme weather event, like drought. The water levels in the river fluctuate due to natural climate variability, but with climate change, the flux in the water levels will become more extreme.

Besides climate change, several aggravating external factors that impact the Rhine's water level can be determined, as shown in the conceptual framework.

For this project, the river landscape of the Rhine will be taken as its leading research area. A river landscape, or riverscape, is defined by Stanford et al. (2017) as '*an expansive view of a stream or river and its catchment, including natural and cultural attributes and interactions*'. Within this riverscape of the Rhine, two types of areas will be used, rural and urban. Rural areas will be defined by their natural characteristics, as found in Pizzoli and Gong (2007). This is done at the hand of land cover profiles (arable, forest, etc.), topographic roughness (mountain, hill, plain) and climate. They define rural as an area that should be mainly covered by agricultural land, forest and natural areas. This definition includes disadvantaged areas for human activities like mountains and extreme climate conditions. In this definition, the natural environment is significantly different for human opportunities and behaviour, between rural and urban areas. With this definition based on the natural characteristics a distinction between the two areas can be made, but there will still be overlaps, where the two areas meet.

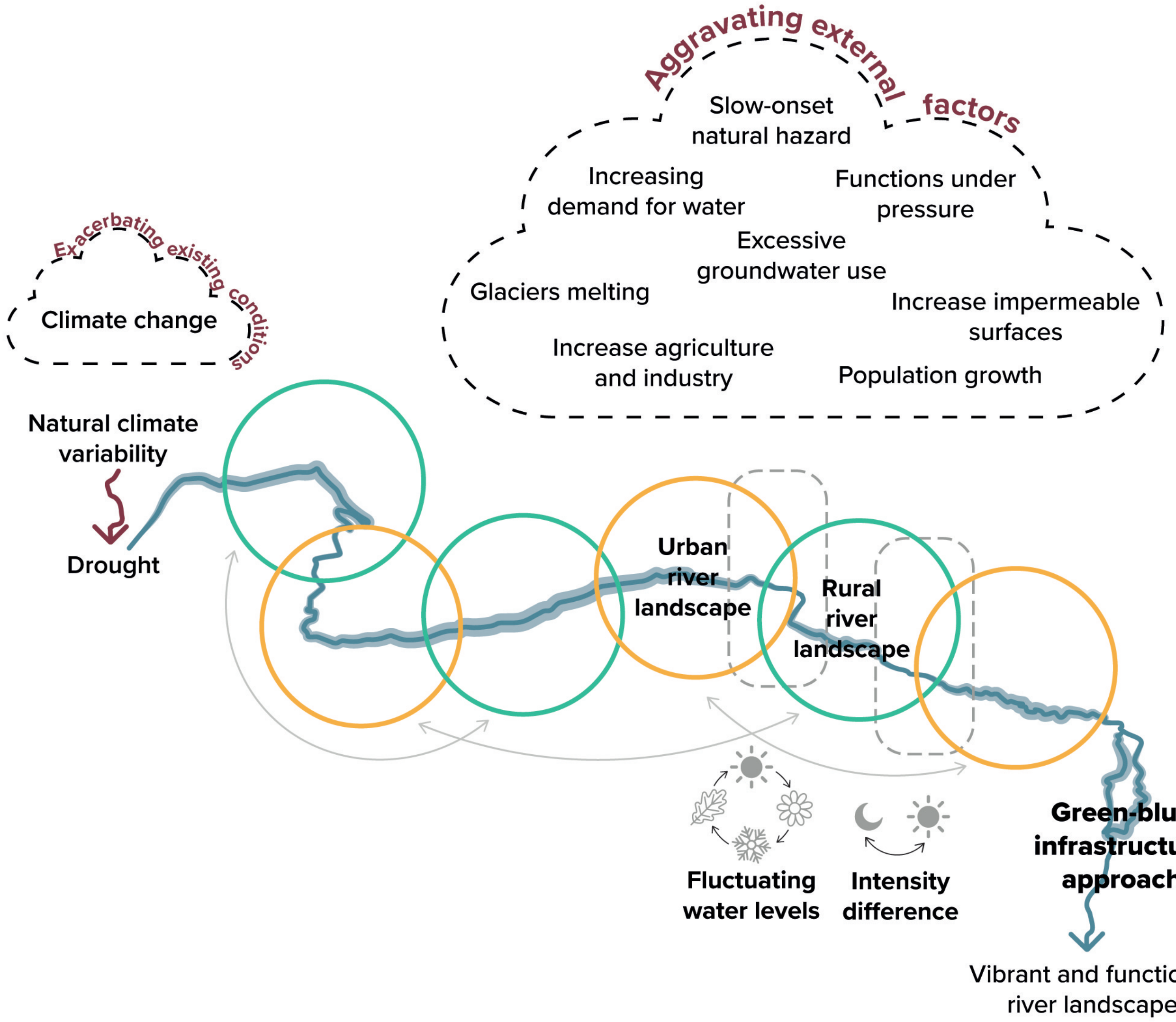


Figure 1.33: Conceptual framework. Made by Author

Finally, the solutions are introduced in the conceptual framework, a green infrastructure-based approach to decrease the impact of drought, leading to a vibrant and functional river landscape.
The European Commission (2013, p. 3) defines Green infrastructure (GI) as '*a strategically planned network of natural and semi-natural areas with other environmental features designed and managed to deliver a wide range of ecosystem services. It incorporates green spaces (or blue if aquatic ecosystems are concerned) and other physical features in terrestrial (including coastal) and marine areas. On land, GI is present in rural and urban settings'*. The approach will cross ecological and political boundaries when using GI in spatial planning. The GI approach *'looks for connections between different elements of nature in the geophysical area, between nature and people's quality of life, across ecological and political boundaries, and across policy sectors'* (ESPON EGTC, 2020, p. 18).
The cross-border approach of green infrastructure fits with the Rhine case study. Creating a vibrant and functional riverscape along the Rhine aims to look for connections between nature and people's quality of life. With the decline of wildlife in Europe, using a green infrastructure approach to decrease the impact of drought will benefit the living conditions of the people around the Rhine. The strategy with a green infrastructure approach will be applied to two design locations, Mainz and Mannheim, marked with grey dotted lines in the conceptual framework. One of these locations will be an urban area, as this will be a complicated location where the strategy has to be tested. The second location will be the area where urban and rural meet. This area will have some interesting implications that will be investigated during the design phase.

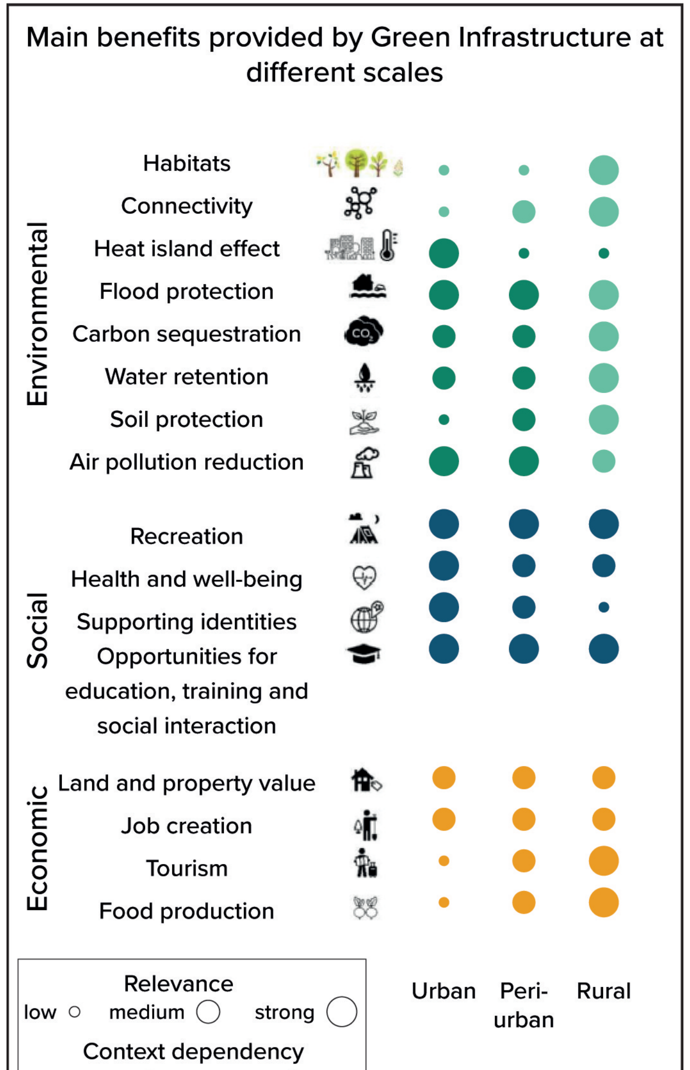


Figure 1.34: Based on ESPON EGTC (2019)

Resilience theory

Holling (1973) first introduced ecological resilience in his paper. He described ecological resilience as the amount of disruption an ecosystem can cope with before it starts to change processes and structures. It is the adaptable capacity of an ecosystem.
Humans are intertwined in this ecosystem and depend on them for their well-being. Nature is constantly changing, and unanticipated events can occur at any time. With climate change, unpredictable events can occur more frequently or more severely, leaving current resilient ecosystems exposed and unable to recover (Eslamian & Eslamian, 2016; Holling, 1973).
Preparing ecosystems for drought events can reduce and sometimes eliminate the effect of drought on the ecosystem. In creating resilience in the case of drought, the focus lies partly on the prediction of drought events and on the reduction of the impact of drought events (mitigation). Different thresholds are essential to consider in order to prepare an area for drought. What types of water sources are vulnerable to drought, what crops are there, the natural ecosystem and the kind of forest are all things to consider and create a different outcome in drought mitigation strategies (Eslamian & Eslamian, 2016).

Systemic design

Systemic thinking is a combination of Design thinking and systems thinking. Combining these interdisciplinary fields opens up more possibilities for understanding complex systems. With Systemic thinking, a design process should include phases of divergence and convergence. This process can start even when the intended outcome is not clear. But Systemic thinking is not a process in itself. It is a way to understand dynamic complexity and generate innovation and value creation (Ryan, 2016; Wandl, 2022).

Next to phases of divergence and convergence, a design process with systemic thinking should be an iterative process that continuously improves. Systemic thinking helps with discussing concrete actions by using the following multiple steps. The steps are; (1) research stakeholders (network); (2) Define the system, problems and challenges should be defined, and the amount should be limited; (3) Map the system, common needs between stakeholders should be described. They should be addressed before individual needs; (4) Choose leverage points; (5) Ideate solutions; (6) Prototype solutions; (7) Test; (8) Evaluate results. These steps are pictured in figure 1.34.
When following these steps, spatial quality will be part of the discussion early on to avoid complications during the implementation phase (Wandl, 2022).

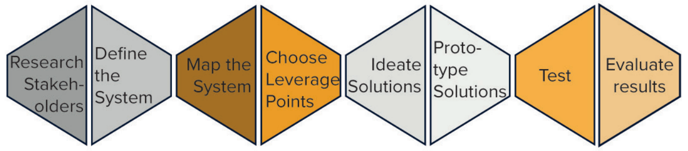


Figure 1.35: Based on Wandl (2022)

DESIGN OBJECTIVE

The thesis Every Drop Counts aims to create a resilient river landscape during streamflow drought. The riverscape of the Rhine will have to deal with more extreme fluctuations in water levels and more intense periods of drought and flooding. These fluctuations will affect the living-, economic-, and recreational conditions around and on the Rhine. To battle these problems, this thesis attempts to create a pattern catalogue focusing on drought-mitigating design strategies. These strategies are implemented around the Rhine and will generate a riverscape to deal with streamflow fluctuations.

Besides creating a resilient riverscape during streamflow drought, the design strategy will have other positive benefits. With the adaptation of the riverscape for streamflow fluctuations, the living conditions around the Rhine will be improved. Flooding of urbanised areas can be avoided, and living and recreational spaces will stay functional during periods of drought. Industries, agriculture and thus the economy around the Rhine will remain functional during periods of drought, as water retention capacity will be increased.
By implementing the drought-mitigating pattern catalogue, habitat diversity will develop and improve biodiversity. The green-blue infrastructure creates a connected structure of habitats where species can flourish. Part of this strategy will be restoring historic riverscapes, creating more space for the Rhine and bringing back old habitats that got lost during the reconstruction of the Rhine.

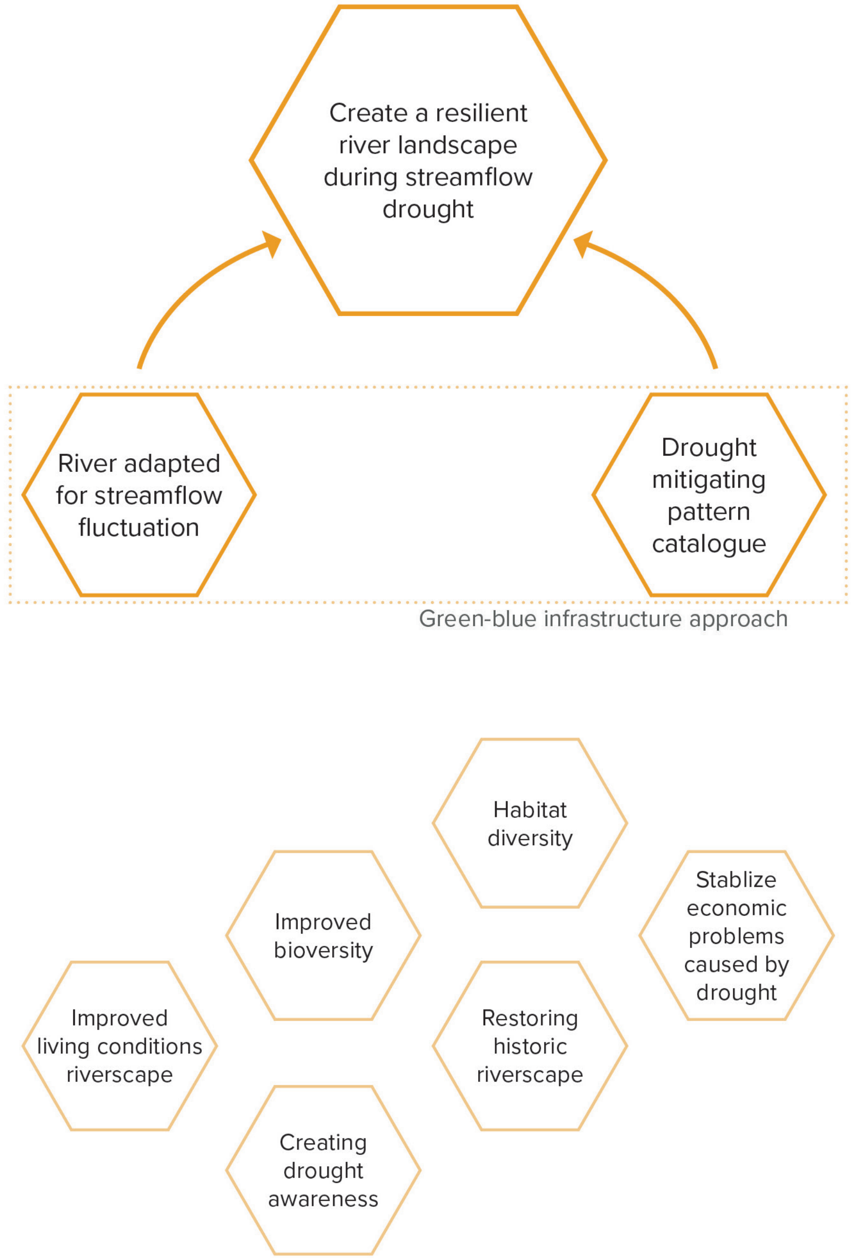


Figure 1.36: Design objective. Made by Author

1.6 METHODS

RESEARCH APPROACH

Main research questions

How can the river Rhine stay a vibrant and functional riverscape by creating a synergy between urban and rural areas while using the green-blue infrastructure approach to prevent drought-related problems?

General outcomes

Analyses that describe the streamflow of the Rhine and the impact of climate change on the streamflow, functions and landscape surrounding the Rhine.
A vision for the Rhine, showing the synergy between river landscapes and large-scale drought prevention measurements.
Strategy with a green infrastructure approach to creating drought prevention measurements for river landscapes. Test the strategy on two design locations.

	Objectives	Problem statement	Sub-research questions	Methods	Outcomes & goals
Analysis	Understanding the environmental impact of drought on the Rhine	Natural climate variability; Increasing demand for water; climate change	SQ1: How does streamflow drought impact the Rhine and the surrounding landscapes?	Literature review; mapping; data collection; site visit; mapping; photo evidence	General knowledge of how the water system and water cycle work and what the leverage points are. Getting to know the river Rhine streamflow. Understanding the effects of climate change on the Rhine streamflow and what impact this will have on the streamflow and surrounding landscape now and in the future.
Analysis	Understanding the social impact of drought on the Rhine	Natural climate variability; Functions under pressure; population growth	SQ2: How are the functions of and on the Rhine affected by drought?	Literature review; data collection; mapping; site visit	Understanding the functions taking place on the Rhine and in the landscape surrounding the river. Determine the importance of the functions and the impact these have on society. Describe the requirements of the streamflow to continue to perform these functions in the future.
Design	Finding solutions to combat the impact of drought on the Rhine	Vision	SQ3: How can the green-blue infrastructure approach be used to form a synergy between urban and rural river landscapes?	Literature review; (historic) mapping	Describe the influence urban and rural riverscapes have on the water cycle, particularly in combination with drought. With this information and the analyses, determine the synergy between the urban and rural riverscapes along the Rhine and how this could change in the future.
Design		Strategy	SQ4: How can nature-based solutions be used for drought-mitigating strategies along the Rhine?	Literature review; photo evidence; case studies	Determine how the green infrastructure approach can help with drought prevention around the river landscape. Describe their effectiveness and implementation requirements. Create strategies with a green infrastructure approach for the river Rhine.
Design		Design	SQ5: How can the desired drought-mitigating strategies be implemented along the Rhine?	Case studies; literature review; strategy	Creating designs along the Rhine to show the implementation of the strategies created. Use this to adjust the strategies as necessary.

Figure 1.37 Research approach, made by Author

METHODS OF APPROACH

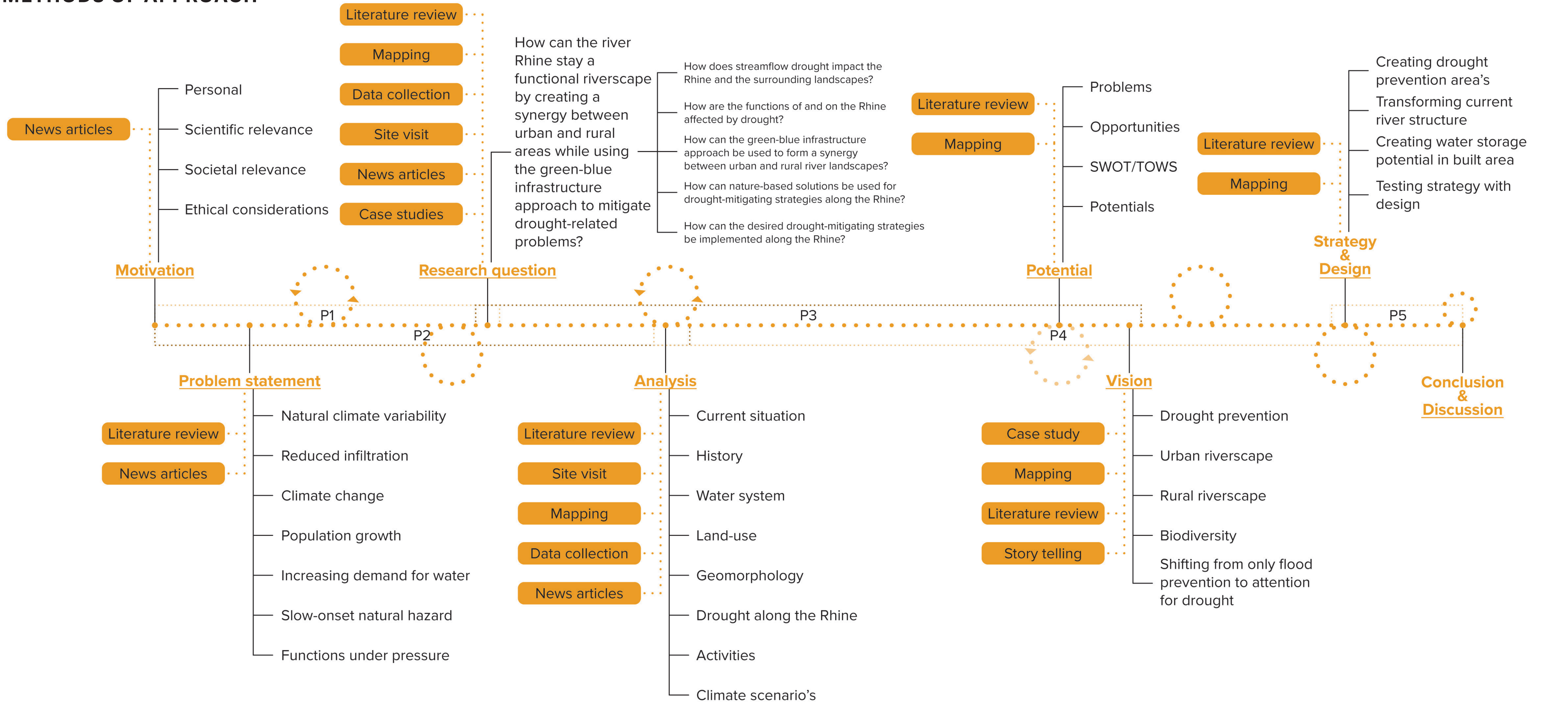


Figure 1.38 Method of approach, made by Author

FROM ANALYSES TO STRATEGY

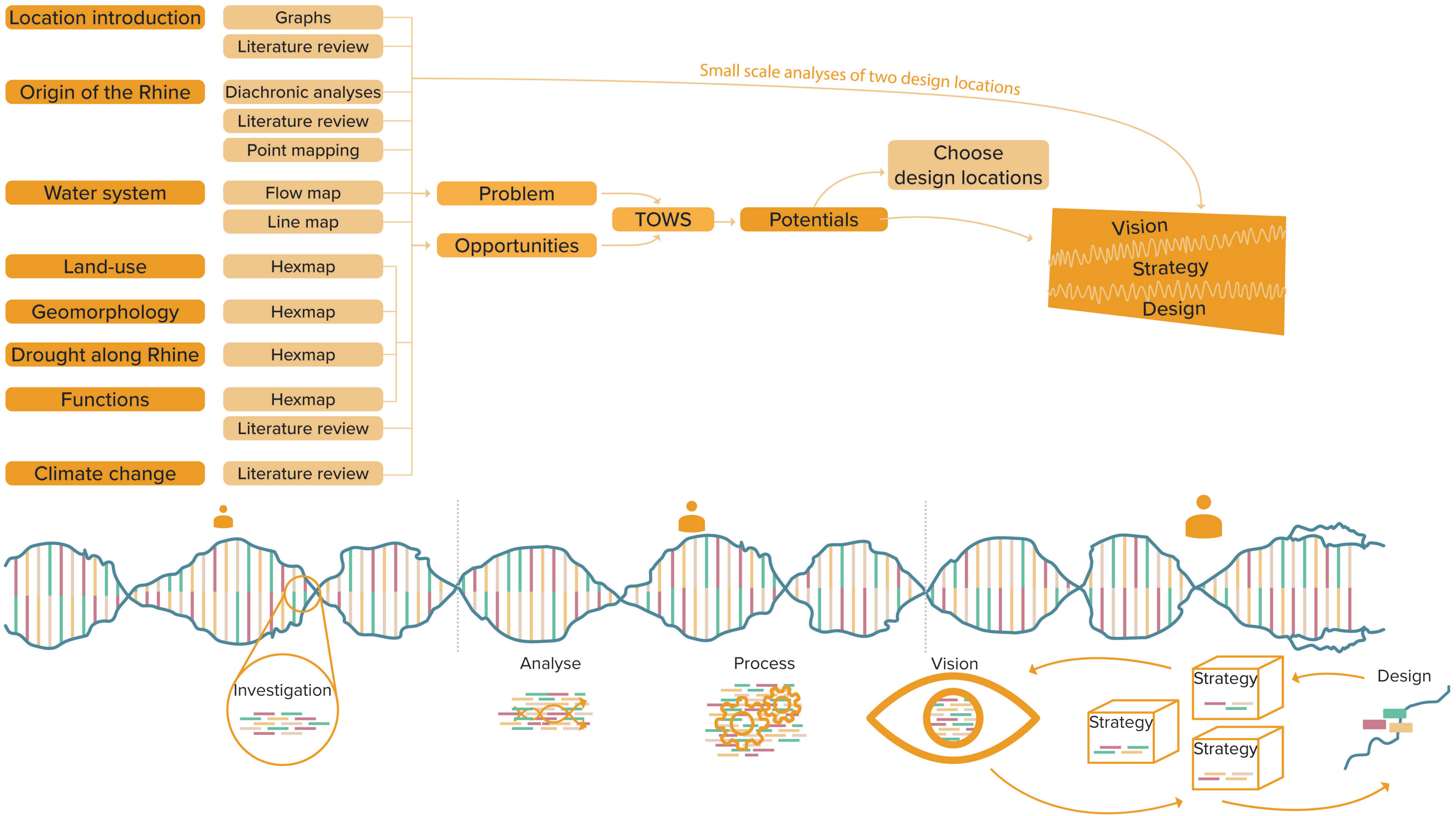


Figure 1.39 From analyses to strategy, made by Author

Objectives, outcomes & goals
The research is separated into three objectives, as shown in the research approach. (1) understanding the environmental impact of drought on the Rhine, (2) understanding the social impact of drought on the Rhine, and (3) finding solutions to combat the impact of drought on the Rhine. The first objective focuses on the increasing demand for water and climate change's impact on this. The streamflow of the Rhine will be affected, and the environmental impact on the functionality of the Rhine will be explored. The outcome of this objective is an understanding of the water cycle, the streamflow of the Rhine and the impact climate change will have on this. Furthermore, understanding the impact these changes have on the surrounding riverscape and the influence the surrounding riverscape might have on the streamflow of the Rhine.

The second objective focuses on drought's social impact on the riverscape. The functions connected to the Rhine will be explored and assessed. The requirements for the streamflow will be determined for each of the functions. These requirements can be used to test the proposed strategic interventions later on.

The third objective focuses on the proposed solutions. This objective aims to find a synergy between the different riverscapes, determine the strategic interventions that can occur with a green infrastructure base, and implement the interventions to design locations along the Rhine to test their functionality. The final result should be a vibrant and functional Rhine riverscape.

From analyses to strategy
The route this research will take is shown in the method of approach. The study starts with an analysis to explore, understand and interpret the Rhine's streamflow, the functions surrounding the Rhine and on the Rhine itself, and the geomorphology of the Rhine. Lastly, the changes in the streamflow and the functions due to climate change will be explored.

All building blocks along the Rhine built up the identity of the Rhine. The analysis for the Rhine will result in different building blocks per area of the Rhine, like in a DNA string (figure 1.38). These building blocks will be brought back into the strategy and can then be compared to the analysis. The type of building blocks suitable for a specific strategy will help determine which will suit a design for a particular location along the Rhine. This way, the different areas of the Rhine can be categorised, and the strategies can be matched during the design phase.

Between the chapter analysis and strategy is the subchapter potentials. This subchapter will help to determine the vision and design locations. First, an overview of the leverage points will be made. Secondly, a map with the problems the Rhine faces in terms of staying a vibrant and functional river landscape, will be combined into one map. This map will determine the points along the Rhine with the highest risk of no longer being functional. A second map, the opportunities map, shows areas with high potential for harbouring potential drought prevention measures.

The next step is using the TOWS analysis based on Weihrich (1982) (figure 1.40). TOWS stands for Threats, Opportunities, Weaknesses and Strengths. First, these different factors need to be determined to use this analysis. Threats and weaknesses can be identified through the problem map. The opportunities and weaknesses can be found in the opportunities map. A TOWS analysis shows the relationships between these different factors. The opportunities with strengths will be identified, threats will be prevented with strengths, opportunities will be used to minimise weaknesses, and potential pitfalls where threats and weaknesses meet will be minimised (Weihrich, 1982). By going through these steps, pitfalls and potentials can be identified. These potentials will be shown in the last map and be the foundation for the vision on a regional scale.

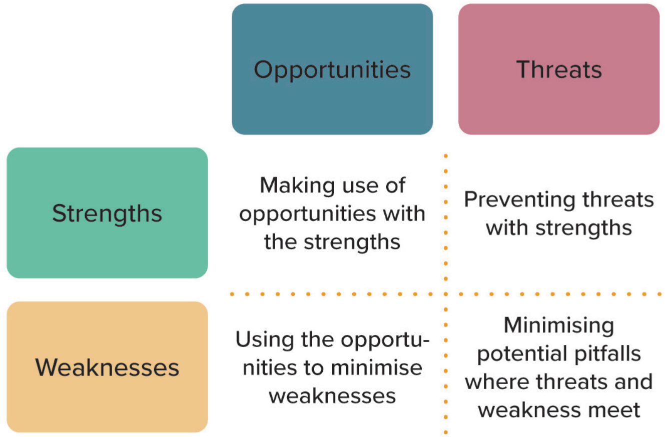


Figure 1.40: Based on Weilhrich (1982). Alterd by Author

ANALYSIS

2.

Figure 2.1: Figures and cattle in a mountain landscape with the Rhine (Barend Cornelis Koekkoek, 1862)

2.1 INTRODUCTION OF THE RHINE

The river Rhine is one of Europe's most iconic water ways. The catchment of the Rhine weaves trough nine countries, having shaped their landscapes and sustained populations and industries.

The Rhine catchment entails approximately 185.000 km2. This catchment spans portions of Switzerland, Lichtenstein, Austria, Germany, France, Luxembourg, Belgium, the Netherlands, and Italy. The international reaches of the Rhine highlight the transboundary of the river, connecting different cultures and landscapes in between.

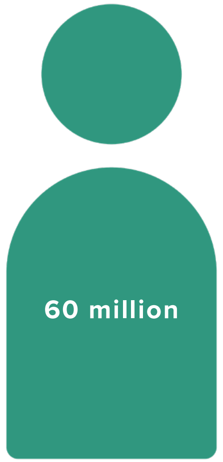
Stretching across approximately 1230 km, the Rhine is one of Europe's longest rivers. The official length can be discussed as multiple starting points are identified, such as the Vorderrhein and Hinterrhein in Switzerland. For some research, Lake Constance (Bodensee) is determined as the starting point of the Rhine.

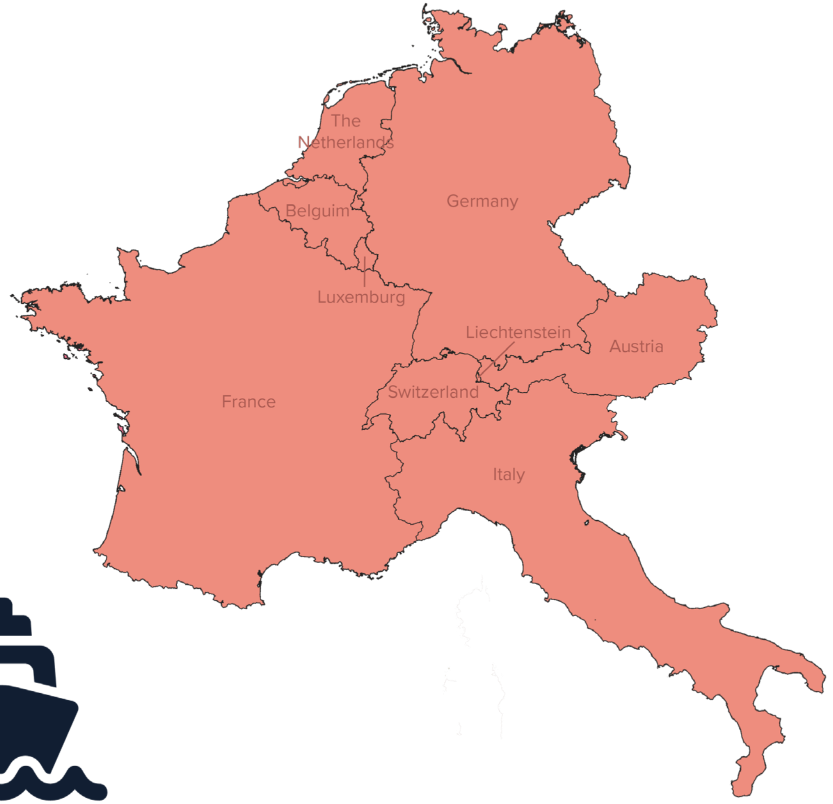
Numerous tributaries (figure 2.2) feed into the streamflow of the Rhine. Notable tributaries are Vorderrhein, Hinterrhein, Thur, Aare, Ill, Neckar, Main, Nahe, Moselle, Wied, Sieg, Ruhr, and Lippe. These rivers merge with the Rhine at various points along its course. The tributaries shape the catchment area of the Rhine, creating valleys and adding to the streamflow. They are essential to the Rhine's water levels and significantly influence droughts and floodings.

The catchment of the Rhine supports a substantial population of approximately 60 million people. The Rhine is an essential source of drinking water for part of these communities. Industries along the Rhine have thrived, making it one of Europe's most vital economic lifelines. The reach of the river and its navigability have attracted numerous industrial activities ranging from manufacturing and logistics to energy production. The Rhine's water is used for cooling processes within the industry and as means of transport. With this, the Rhine has become a vital part of the industries of its catchment area.

For effective management, the Rhine has officially been divided into six sections. Namely, Alpine Rhine, High Rhine, Upper Rhine, Middle Rhine, Lower Rhine, and Delta Rhine. The division has been made based on hydrographical and natural characteristics. Each region has an agreed-upon water management strategy.

The Rhine River is a magnificent waterway with immense importance for Europe. With the extensive catchment, numerous tributaries, and its source for drinking water and industry, The Rhine holds a central role in the lives of millions of people.





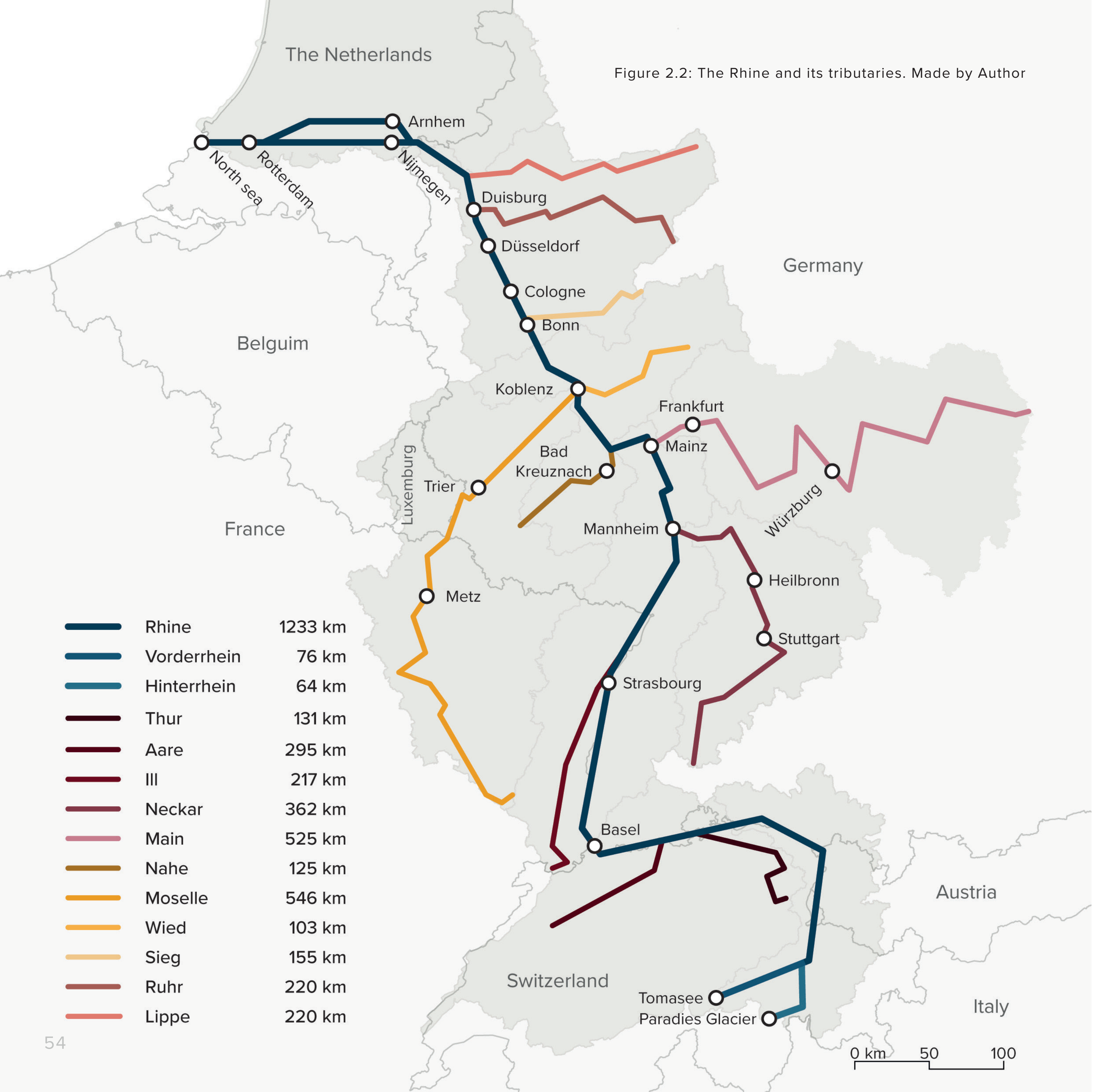


Figure 2.2: The Rhine and its tributaries. Made by Author

Figure 2.3: The Rhine in pictures. Collage made by Author

2.2 ORIGIN OF THE RHINE

For this section, a timeline (figure 2.6) with significant events around the Rhine has been created. From 8000 BCE till current times, many different events occurred, like reconstructions of the Rhine, many severe floods and drought events. Next to that, governmental decisions have also been added to this timeline.

19th-century reconstruction of the Rhine
Between 1817 and 1876, reconstructions of the Rhine significantly impacted the flow regime. The reconstructions, as envisioned by Johann Gottfried Tulla, a German engineer, transformed the river into a more efficient transportation route while reducing the destructive effects of flooding. For this reconstruction, a systematic river channelization approach was implemented. The riverbed was deepened and straightened. Obstacles were removed, sometimes this involved blowing op rock formations, and bank stabilizations were put into place. These modifications enhanced the navigability of the Rhine, reducing travel times and providing a more predictable and consistent flow (Wasserstrassen- und Schifffahrtsverwaltung des Bundes, n.d.).

The reconstruction was not without its problems. The restructuring of the Rhine had an enormous impact on the environment and habitats along the Rhine. By modifying the river's natural course and implementing bank stabilizations, the natural ecosystem of the Rhine was disrupted. Flow patterns changed, and habitats were affected. Species dependent on these habitats where lost around the Rhine. Communities had to be moved to make room for the reconstruction. With the loss of habitats, natural water retention has been diminished, and the river has less room during flooding events as artificial surfaces have increased since the 19th century. Now, decades later, the consequences of flood and drought are also noticeable.

ICPR
The International Commission for the Protection of the Rhine (ICPR) was established in 1950. The first countries involved where Germany, France, Luxemburg, the Netherlands, and Switzerland. The organisation's goal was to analyse the river Rhine's pollution and recommend measures for water protection. The founding countries aimed to share monitoring data and analysis methods. The ICPR succeeded in international cooperation and established legally binding conventions (International Commission for the Protection of the Rhine, n.d.).

Chemical spill
The Sandoz chemical spill took place in 1986 in Basel, Switzerland. The spill had far-reaching consequences for the environment along the Rhine. This event has raised awareness about the importance of proper industrial waste management. A fire broke out in a warehouse owned by Sandoz, a pharmaceutical company. The fire quickly spread, and when trying to put out the fire, water was spilt into the Rhine with the toxic chemicals. This spill had severe consequences for the aquatic ecosystem. Countless fish and other organisms died because of the spill. The spill turned the water red and made the river water temporarily unsafe to consume, disrupting the drinking water supply for millions of people. The incident fostered international cooperation and led to the creation of the Rhine Action Program, which aims to protect and restore the river's ecosystem (Environment & Society Portal, n.d.; Plum & Schulte-Wülwer-Leidig, 2014).

Figure 2.4: Aftermath of Sandoz chemical spill (Badische Zeitung/dapd, 1986)

Figure 2.5: Rhine channel (Vimont, n.d.)

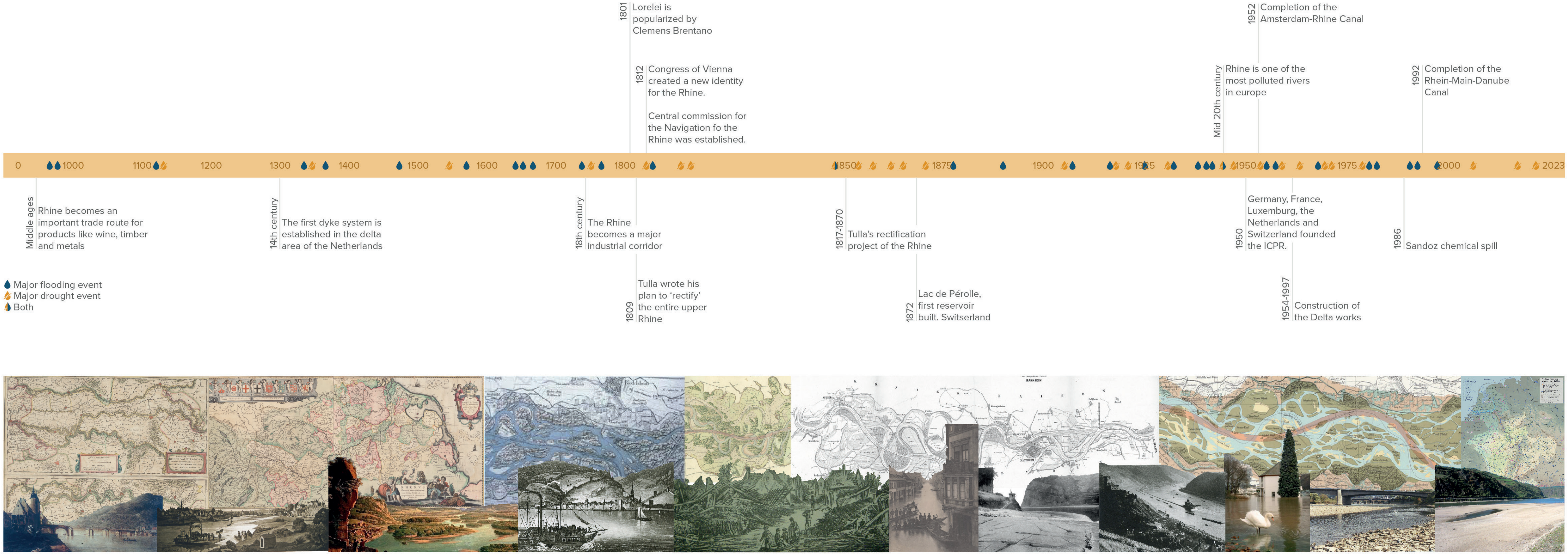


Figure 2.6: Timeline of the Rhine. Collage made by Author

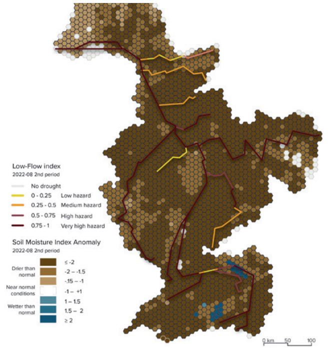
2.3 DROUGHT ALONG THE RHINE

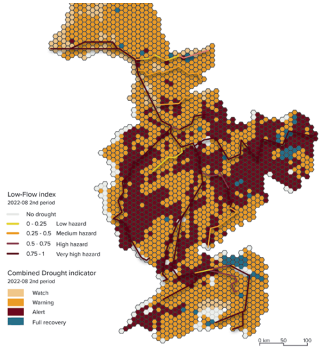
The Rhine is facing significant challenges due to climate change. One of the more concerning impacts is the variation of streamflow patterns, particularly the increased risk of drought events. The Swiss Alps and its glaciers feed the Rhine basin. However, rising temperatures are causing glaciers to melt, leading to an increase in melting water and, finally, a lack of this melting water.
During the first warmer month, glaciers and their snowpack start to melt, contributing to the streamflow and maintaining a stable water table throughout the year. It helps replenish the river during dry periods.

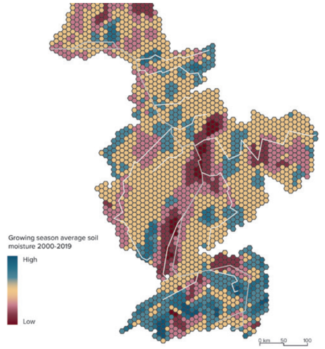
With the glaciers melting, the streamflow patterns of the Rhine will be altered. The change in streamflow patterns has potential consequences for the water availability in the Rhine, especially during dry seasons. The river is changing from a stable glacier river to a more fluctuating rain-based one. A fluctuating water level exacerbates the risk of low-flow periods and increases the vulnerability of the river system during drought events (Internationale Commissie ter Bescherming van de Rijn (ICBR), 2015).

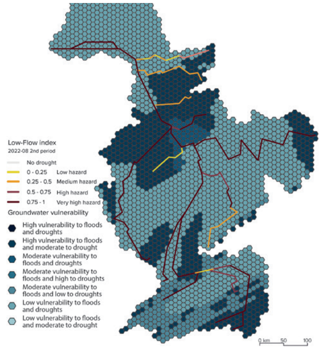
For the drought map, different drought measures have been combined to create an overview of the impact of drought on the river Rhine's catchment. The low-flow index measures the severity and duration of reduced water levels and river flow rates. The occurrence of streamflow drought can be observed with this index. During the summer of 2022, the Rhine was characterized by very high hazards for low flow. The soil-moisture index anomaly shows the effects of climate on soil moisture. It measures deviations from normal soil moisture levels. It assesses the impact of climate change-induced drought on the Rhine River basin (Stahl et al., 2022). The combined drought indicator investigates various climate and hydrological variables and assesses drought conditions. As climate change is likely to increase the frequency and severity of drought, this tool can be a valuable asset in predicting these changes (Görgen et al., 2010). Growing season average soil moisture shows how climate change affects soil moisture availability during the growing season. This measurement shows the direct impact of drought on the agricultural sector. Groundwater vulnerability indicates areas where drought or flood can impact groundwater levels negatively.

When combining these measurements, an overlap between groundwater vulnerability to drought and flood can be seen. Lack of soil moisture is most noticeable around the river Rhine but does not necessarily overlap with groundwater vulnerability.









Maps available in appendix

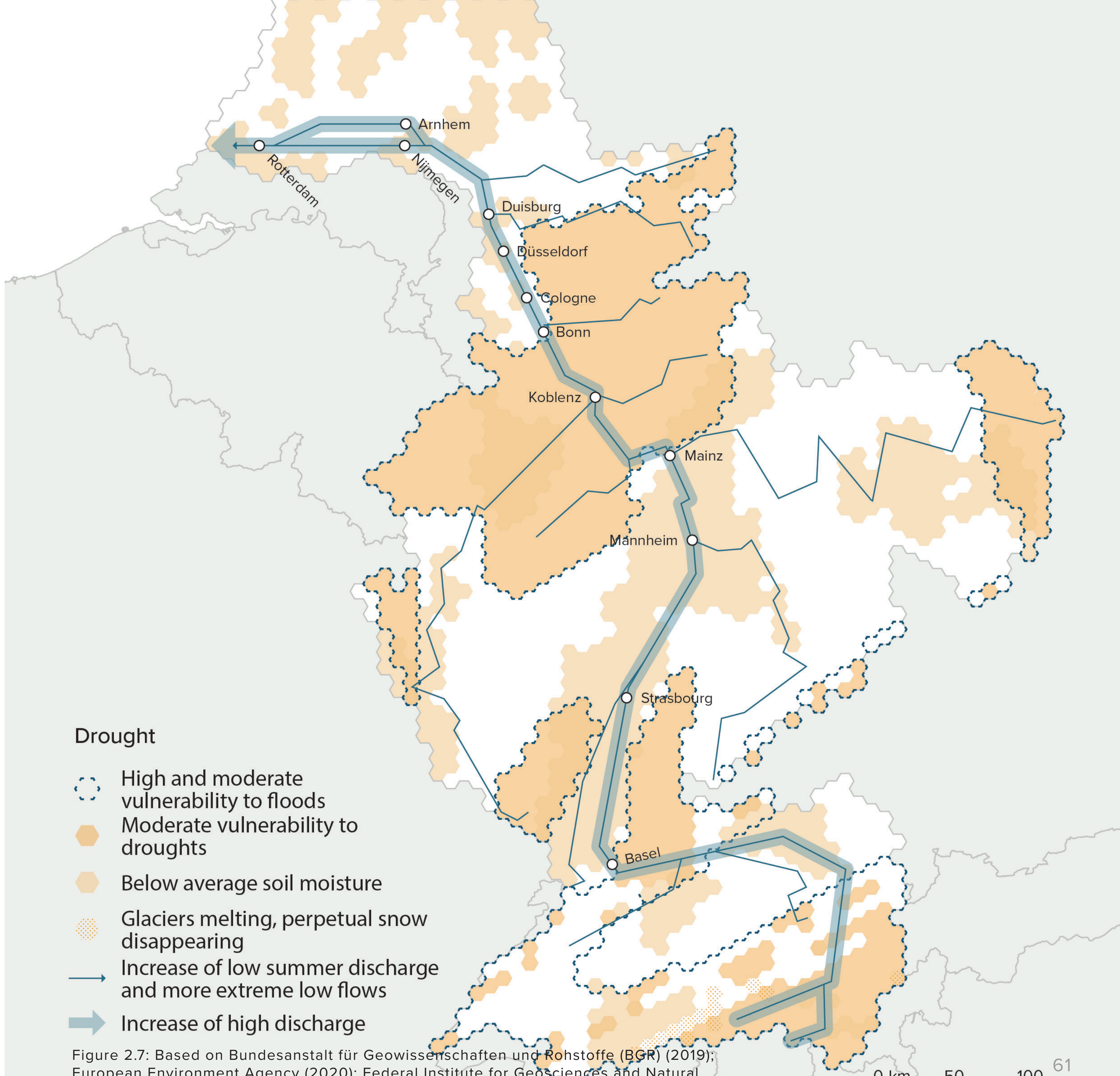
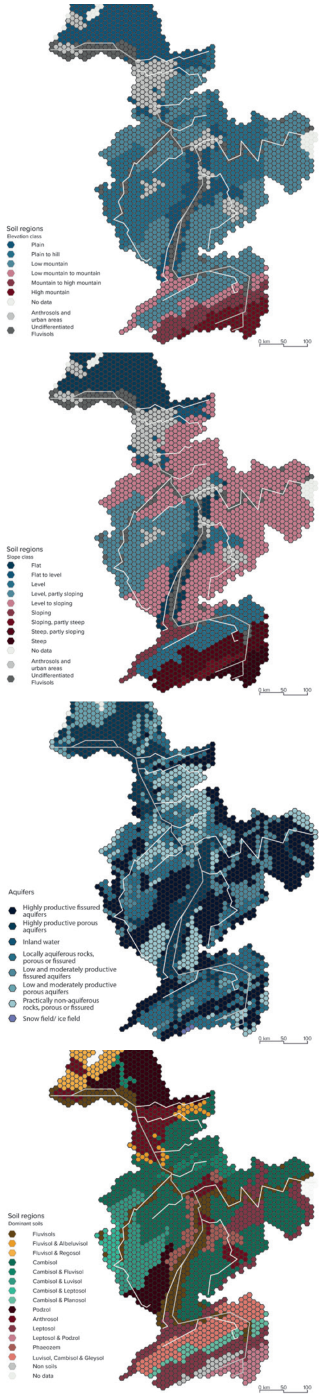


Figure 2.7: Based on Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) (2019); European Environment Agency (2020); Federal Institute for Geosciences and Natural Resources (n.d.); Günther et al. (2019). Alterd by Author

2.4 GEOMORPHOLOGY

The geomorphology types are made up of four elements. Here the slope, elevation, dominant soil, and aquifer type are used to determine eight different geomorphological typologies.
Soil is a dynamic thing that responds to changes in seasons and weather patterns. Europe has a complex and diverse soil type distribution. For this categorization of geomorphology, the types of soil set by the European Soils Bureau Network and European Commission (2005) are used. This analysis was used to find the dominant soil type in the region to reduce the complexity.
For aquifers, the distinction between productive and low and moderately productive aquifers was made. Besides that, two other differences are found: porous and fissured aquifers. Porous aquifers have porous spaces that connect, while fissured aquifers rely on fractures and cracks where water flows through.

Type	Slope	Elevation	Dominant soil	Aquifer
1	Plain	Flat	Fluvisol	Highly productive porous
2	Plain to hill	Level	Anthrosol, Phaeozem	Highly productive fissured
3	Low mountain	Level to sloping	Cambisol, Luvisol	Highly productive fissured
4	Plain to hill	Level, partly sloping	Cambisol	Aquiferous rocks
5	Undifferentiated Fluvisol	Level	Fluvisol	Highly productive porous
6	Low mountain to mountain	Sloping to steep	Lepotsol	Mixed
7	Mountain to high mountain	Steep, partly sloping	Leptosol	Highly productive fissured
8	High mountain	Steep	Leptosol	Mixed



Maps available in appendix

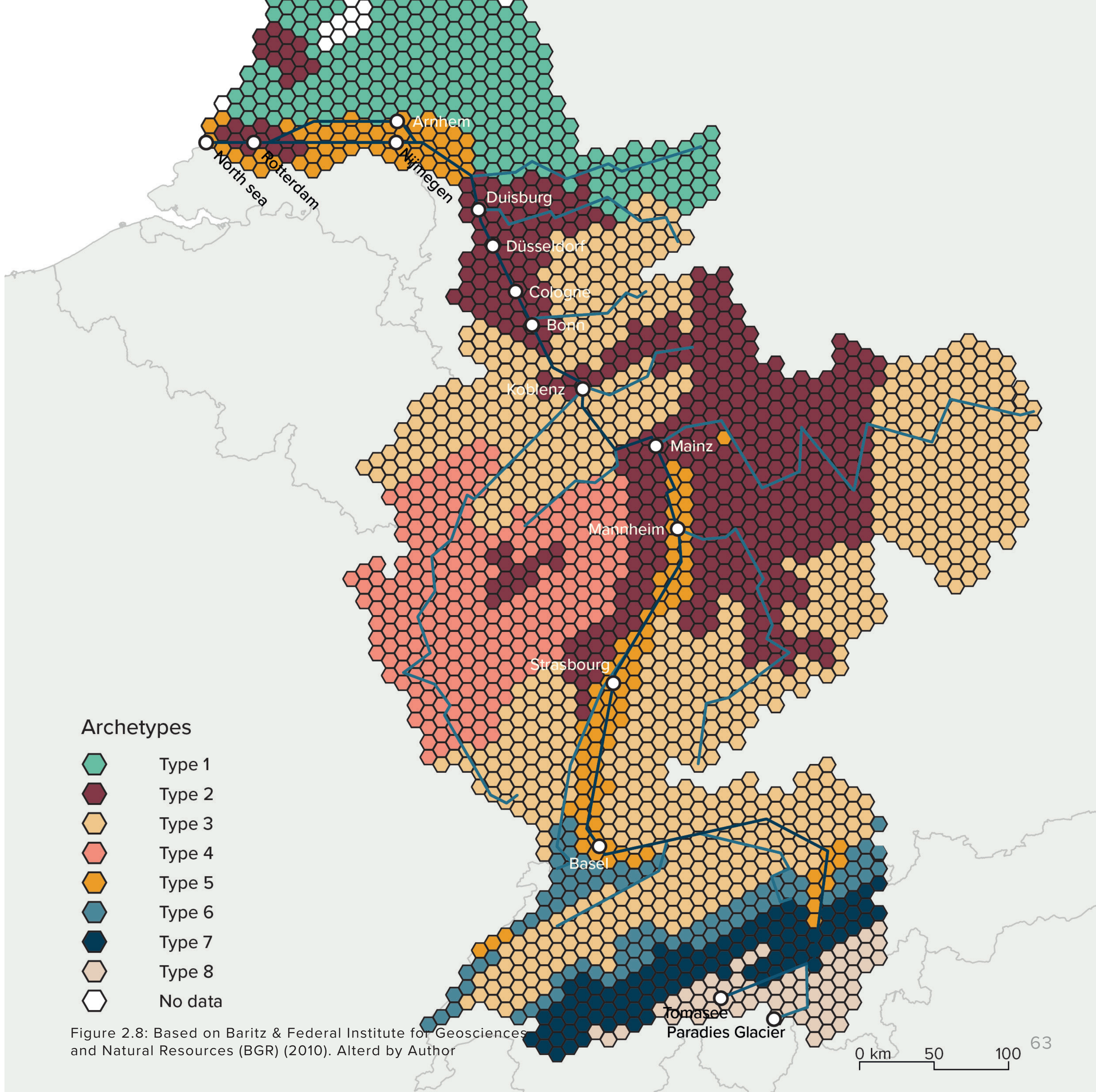
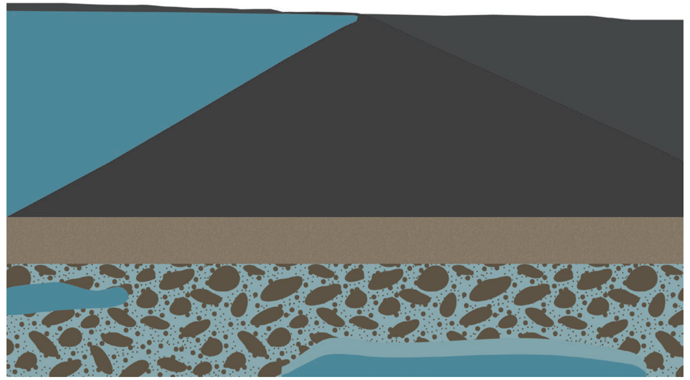
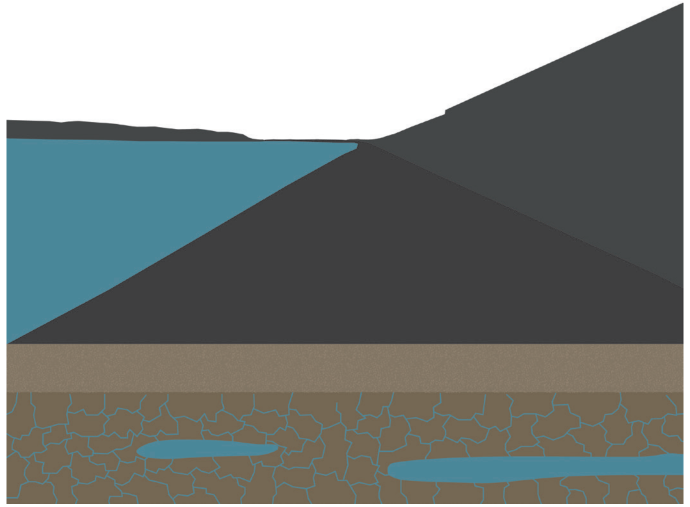


Figure 2.8: Based on Baritz & Federal Institute for Geosciences and Natural Resources (BGR) (2010). Alterd by Author



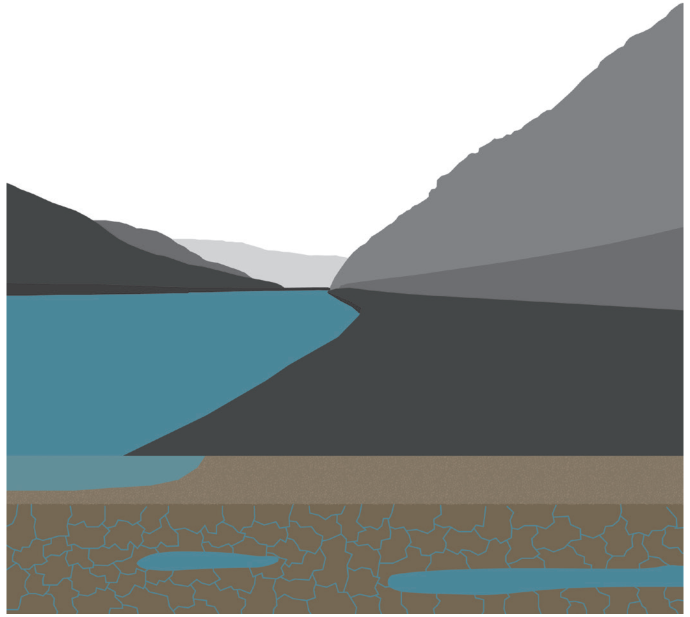
Type 1

Consist of a flat and plain landscape. With this type of landscape, often, less run-off occurs. This landscape is characterized by fluvisol as the dominant soil type. Fluvisols can appear as river sediments, lacustrine and marine deposits. They are often in areas that periodically flood or have stagnating groundwater. This makes this soil type usually wet and has a high water-holding capacity. Fluvisol are suitable for agriculture as they are quite fertile. For this typology, the most prominent type of aquifer is the highly productive porous aquifer, making it ideal for groundwater storage.



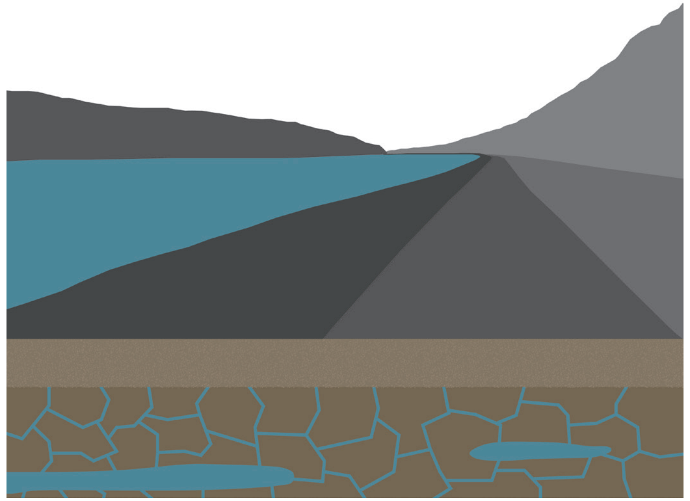
Type 2

Consist of a level landscape with plain to hill slope features. This landscape is characterized by anthrosol and phaeozem. Anthrosol is a soil type that forms as a result of human activity. Most commonly, it is a porous soil. It is frequently used for agricultural practices and mixed with fertilizers to enhance crop productivity. Phaeozem are soils that have percolation, but for phaeozem, the soil can have periods where it dries out. During dry seasons this can lead to a shortage of water in the soil. This can lead to severe problems during periods of drought. Highly productive fissured aquifers characterize this typology and are suitable for storing groundwater.



Type 3

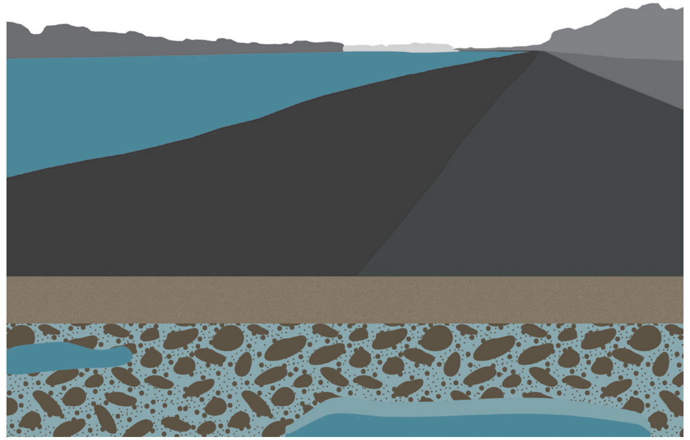
Consist of a low mountainous landscape that has level to sloping elevations. The landscape is characterized by cambisol and luvisol soil types. Cambisol are incipient soil formations. They are reasonably young soil types and will take characteristics of other soil types as they progress. They have good water-holding capacity and excellent internal drainage. Luvisol are commonly linked to cambisol. Luvisol are porous and well-aerated. They drain well but can have shallow groundwater. This typology has highly productive fissured aquifers as the most common aquifer. Combined with shallow groundwater, this may lead to a less optimal situation for groundwater recharge.



Type 4

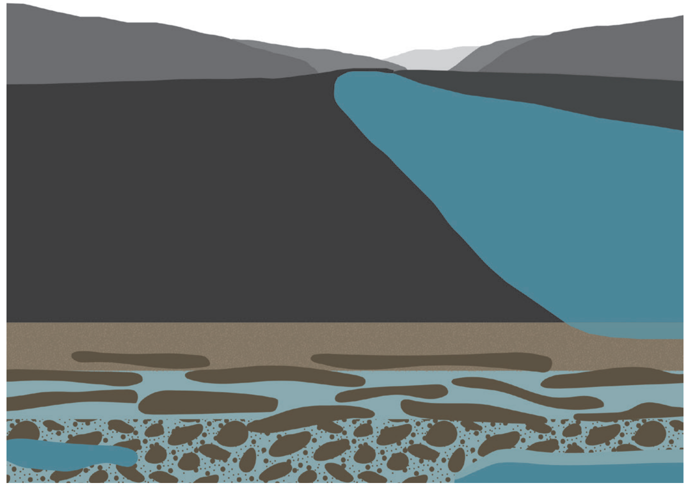
Consist of a plain to hill landscape with partly sloping elevations. This type of landscape can cause more run-off, and lower plains might be more susceptible to rainwater flooding. This typology is most commonly associated with cambisol. As described in type 3, cambisol have good water-holding capacity and excellent internal drainage. The most commonly found aquifer in this typology is the aquiferous rock formation. These are highly productive and have good drainage due to their structure. This can have positive consequences for the recharge of aquifers.

Source from International Soil Reference and Information Centre (n.d.)



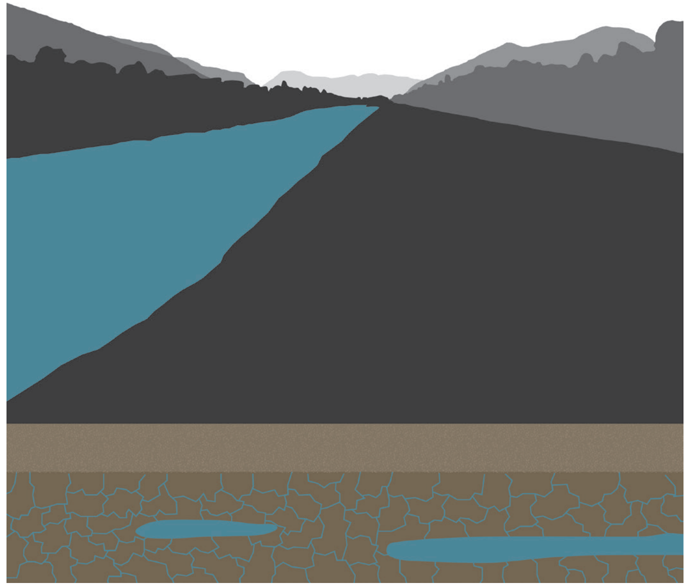
Type 5

Consist of the undifferentiated fluvisol with a levelled elevation making for some run-off towards lower situated areas. As described in type 1, fluvisol are usually wet and has a high water-holding capacity. Fluvisol are suitable for agriculture as they are quite fertile. For this typology, the most prominent type of aquifer is the highly productive porous aquifer, making it ideal for groundwater storage.



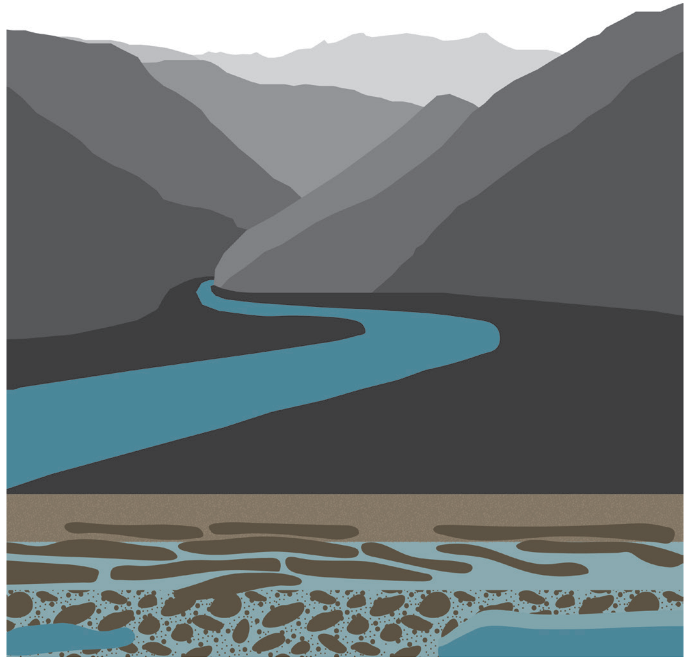
Type 6

Consist of a low mountainous to mountainous landscape with sloping to steep components. This typology is characterized by leptosol. Leptosol is very shallow soil that lays over hard rocks or soil with a gravelly consistency. It is a free-draining soil, meaning that the drainage occurs gradually. It has a low water holding capacity and is unsuitable for arable cropping. When this soil is excessively drained, it can lead to drought events. This is combined with low or moderately productive fissured aquifers, making it highly likely for drought to occur, but also an area where drought prevention measures of a natural basis are hard to implement.



Type 7

Consist of a high mountain area with steep or partly sloping characteristics. This typology is most commonly associated with Leptosol. As described in type 6, leptosol is a free-draining soil with low water holding capacity. When this soil is excessively drained, it can lead to drought events. In this typology, highly productive fissured aquifers are most common but will likely be combined with slow recharge.



Type 8

Consist of a high mountain area with steep characteristics. This typology is most commonly associated with Leptosol. As described in type 6, leptosol is a free-draining soil with low water holding capacity. When this soil is excessively drained, it can lead to drought events. This typology has different types of aquifers, but the soil type is unsuitable for aquifer recharge.

Source from International Soil Reference and Information Centre (n.d.)

2.5 WATER SYSTEM

The river Rhine is fed by a network of tributaries that originate in several different countries. The streamflow of the Rhine is primarily sustained by feeds from the Alpine region and melting snow and glaciers in the Swiss Alps. The most significant contributions from tributaries to the streamflow come from the Aare, Moselle, Neckar, and Main river. This combination provides a continuous water supply throughout the year, but as described in section 2.3, fluctuations in the streamflow are not unprecedented. In figures 2.9 to 2.11, the average discharge of the during high and low water is portrayed.

The water system of the Rhine serves different purposes and plays a crucial role in socio-economic activities in its catchment area. It provides drinking water for millions of people. It supports extensive agricultural irrigation systems, ensuring food production in the region. The industry heavily depends on the Rhine water for their operations, using it as cooling water. And maybe most significantly, the transport of goods and commodities contributes to the economy of the whole of Europe.

The use of the Rhine's water has consequences for its streamflow. Especially during potential drought events, the streamflow of the Rhine is susceptible and extracting more water can increase the problems and intensify the consequence of drought. Water extraction can reduce the water volume significantly if there is no overview of this.

The risk of water abstraction is why it is essential to estimate the use of streamflow water along the Rhine. Water levels are significantly lower during drought events, and they are hardly comparable on the same scale as high water discharge levels. First, an overview of low and high water discharge has been given to give an insight into this (figure 2.9 to 2.11). Here the discharge can be compared to the height profile of the rhine and its banks (figure 2.12). Comparing the height profile with the discharge gives an extra layer of detail as the discharge is measured in m3/s and thus is influenced by sloped areas.
Next to that, there is an estimated water use map made (figures 2.13 & 2.14). An overview is given by comparing the functions along the Rhine with their potential water use during normal and drought conditions. There is an apparent increase in the need for water during drought conditions. The areas with high water usage are often artificial surfaces or agricultural areas. These have the highest water demand. Agriculture especially has a significant increase during drought periods. From this map can be concluded that a limited set for the amount of water that can be extracted from the Rhine might be a future need to keep functions around the Rhine viable.

Low water discharge

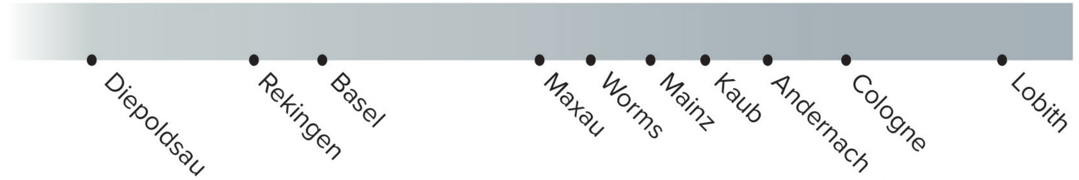


Figure 2.9: Based on ICBR (2018). Alterd by Author

High water discharge

Figure 2.10: Based up Eidgenössisches Departementfür Umwelt, (2021a, 2021b); Gewässerkunde (2022a, 2022b, 2022c, 2022d, 2022e, 2022f, 2022g, 2022h). Alterd by Author

Low water discharge
Second unit

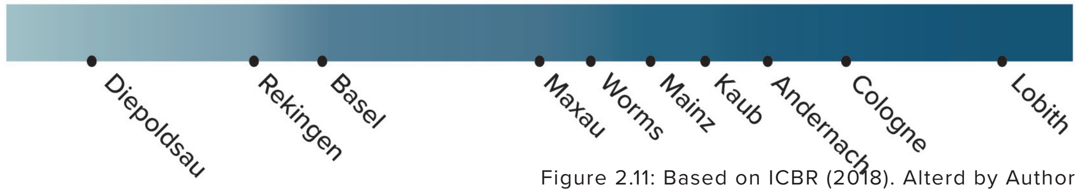


Figure 2.11: Based on ICBR (2018). Alterd by Author

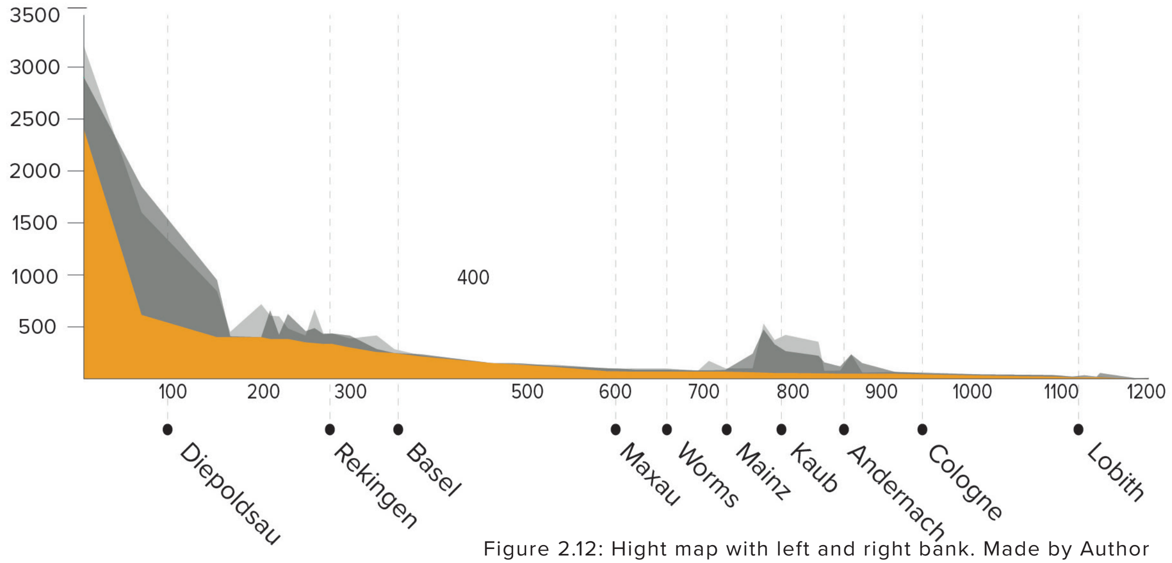
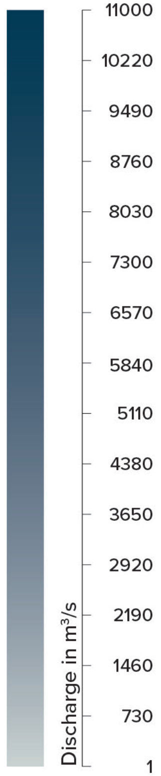


Figure 2.12: Hight map with left and right bank. Made by Author



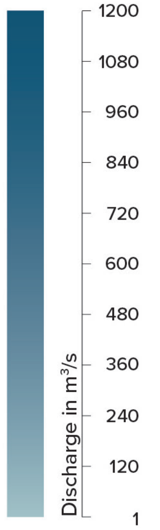


Figure 2.13: Based on Copernicus & Land Monitoring Service (2018). Altered by Author

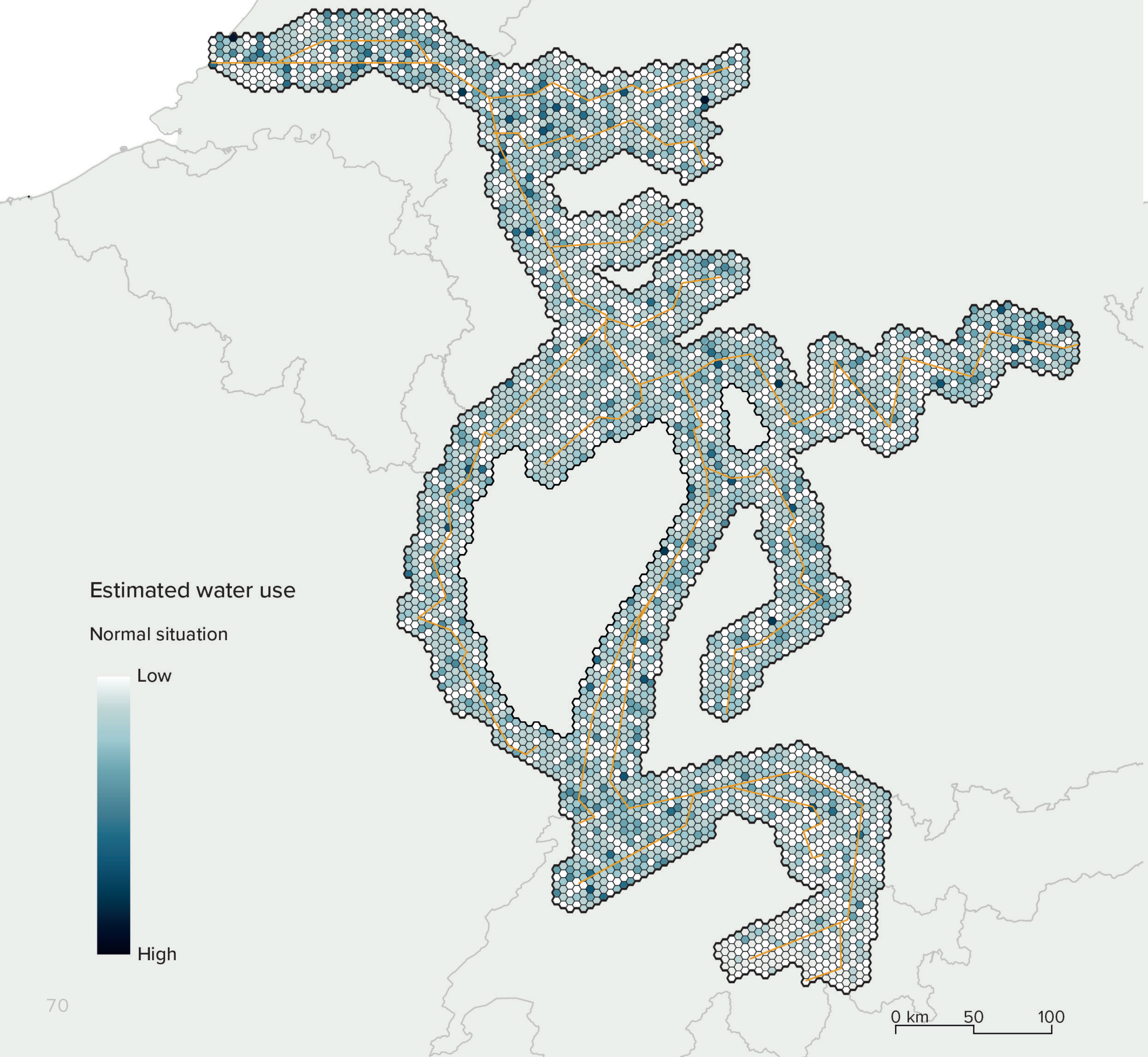
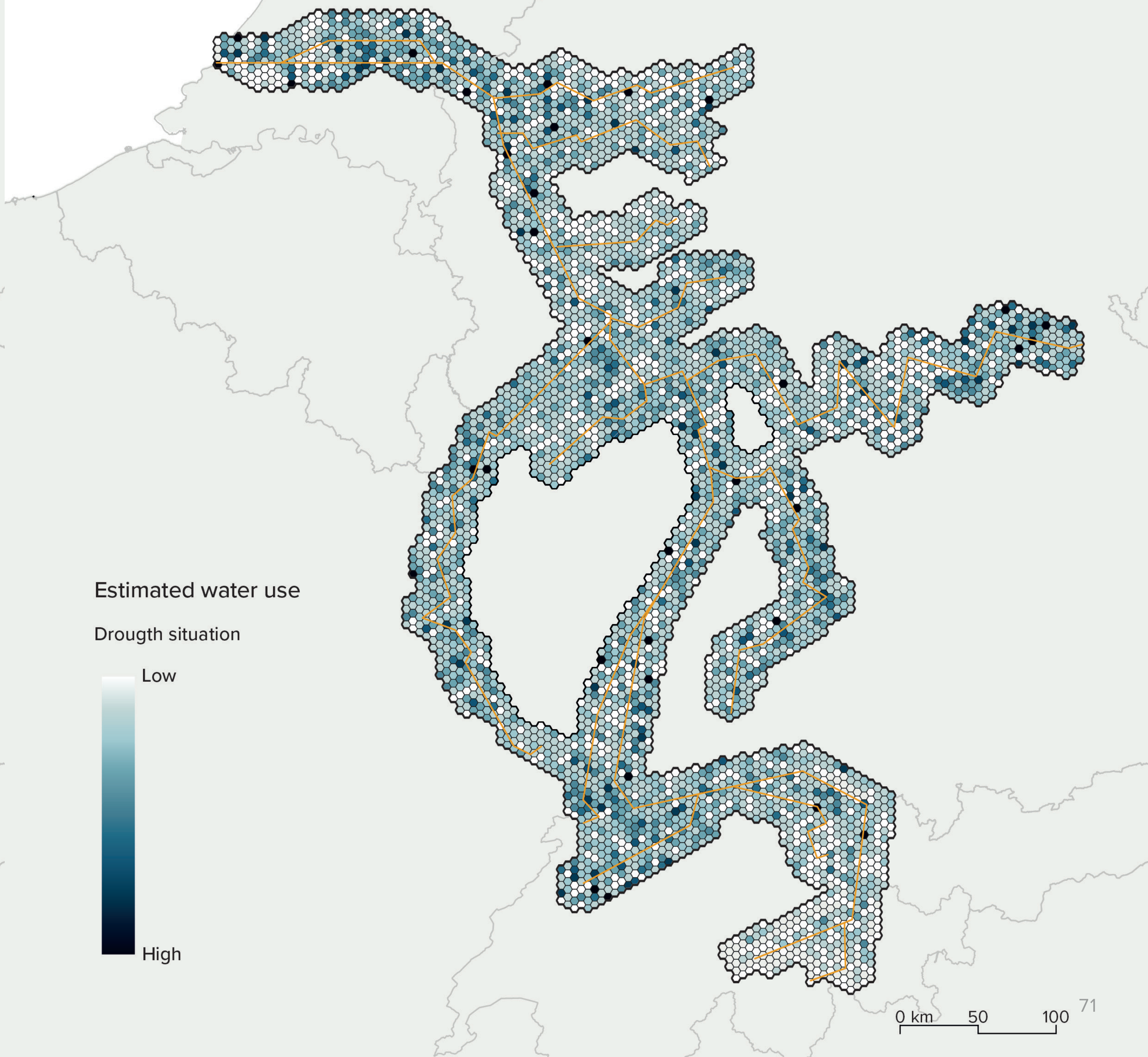


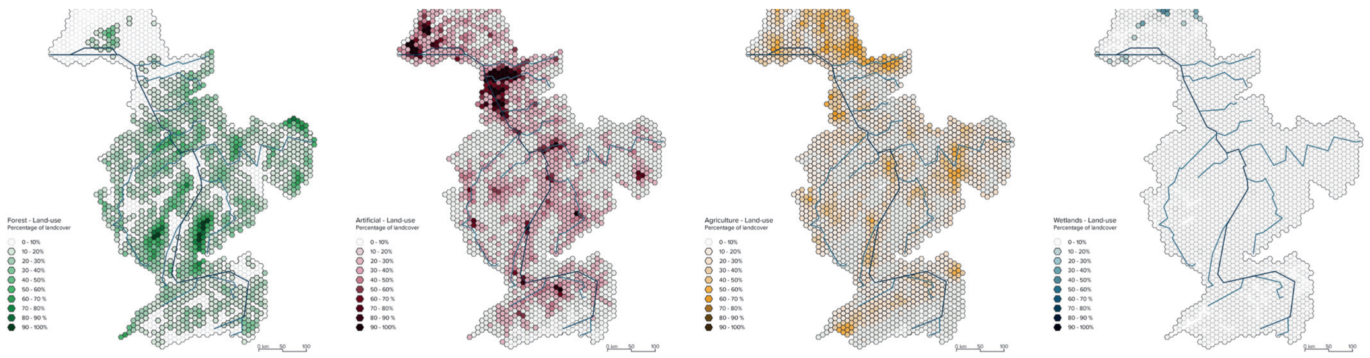
Figure 2.14: Based on Copernicus & Land Monitoring Service (2018). Altered by Author



2.6 LAND USE

This map shows the four most common land uses around the Rhine. By creating a grid structure, the dominant land use per hexagon has been counted and shown on this map. On the map, artificial areas are immediately noticeable around the city marks.
The primary dominant land use around the Rhine is agricultural land. It is also noticeable that forest areas are usually a bit further away from the river. In the end, because of the grid size, there is no dominant land use of wetlands left. The lack of wetlands on this map also implies that wetlands around the Rhine are pretty small and have little impact on their surroundings.

The different land uses consist of multiple land use data. Here is the list of what each land uses consist of:
- Artificial surface consists of the urban fabric, industrial, commercial and transport units, mining, dump and construction sites, and artificial, non-agricultural vegetated areas.
- Agriculture comprises arable land, permanent crops, pastures, and heterogeneous agricultural areas.
- Forest consists of broad-leaved forest, coniferous forest, and mixed forest.
- Wetlands consist of inland wetlands and maritime wetlands.



Maps available in appendix

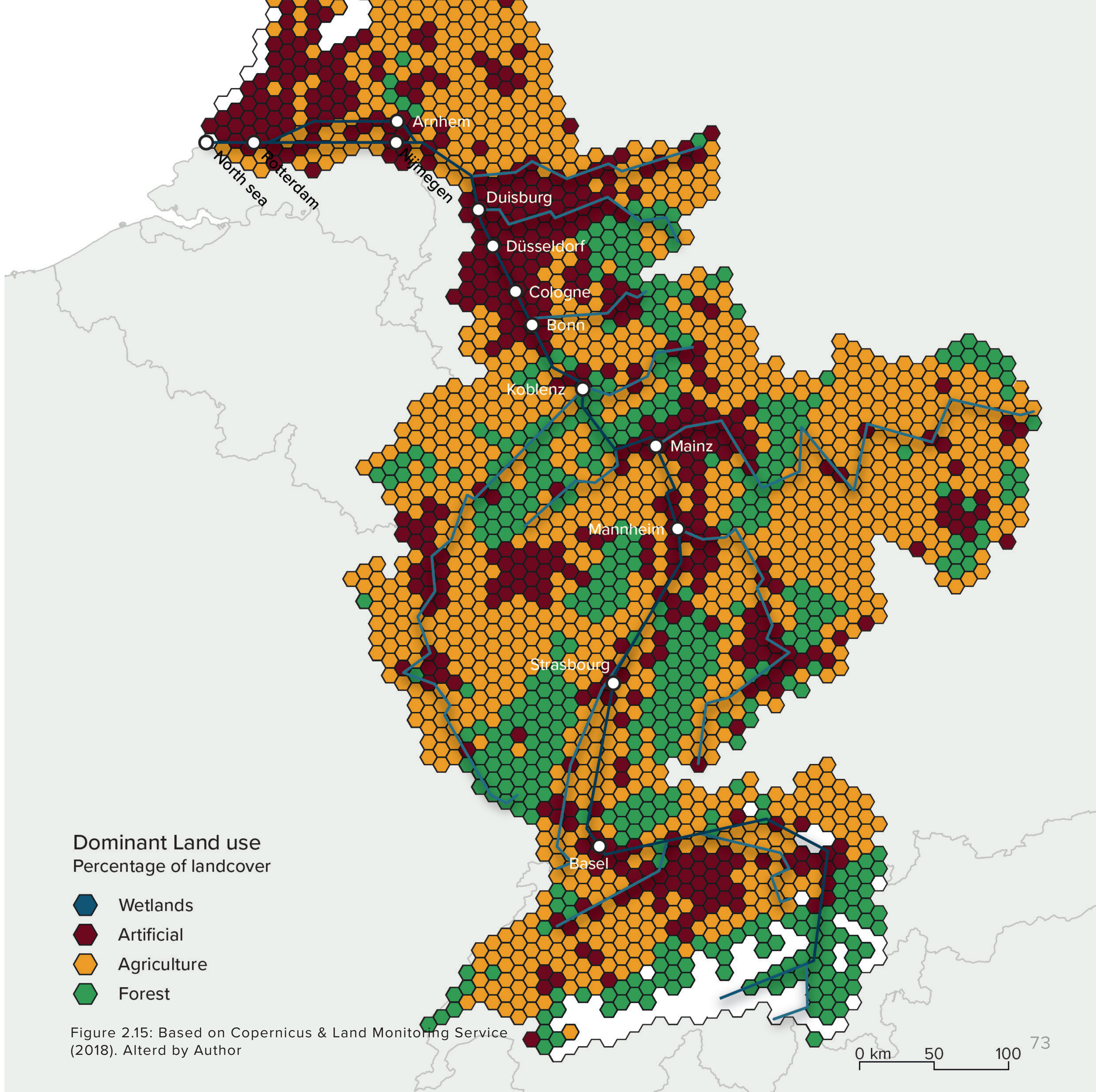


Figure 2.15: Based on Copernicus & Land Monitoring Service (2018). Alterd by Author

2.7 FUNCTIONS

This map shows the different functions that occur along the Rhine. On the map, living functions are seen predominantly near city points. Around the middle Rhine, we see vineyards. Industries are sporadically spread all over the catchment of the Rhine. Recreational functions are often near industrial functions. This cluster implies that in these areas, people also live but that industries are more predominantly present.

The different functions measured on this map come from the Corine Land Cover (2018) data. To create a readable map, different functions are combined into main categories. The following list is what each function consists of to create this main category.
- Recreational consists of green urban areas and sports and leisure facilities.
- Living consists of continuous urban fabric and discontinuous urban fabric.
- Livestock consists of pastures.
- Vineyard consists of vineyards.
- Industry consists of industrial or commercial units, port areas and airports.
- Horticulture farming consists of non-irrigated arable land, permanently irrigated land, rice fields, fruit trees and berry plantations, olive groves, annual crops associated with permanent crops, complex cultivation patterns, land principally occupied by agriculture, and agro-forestry areas.
- Forest consists of broad-leaved forest, coniferous forest, and mixed forest.

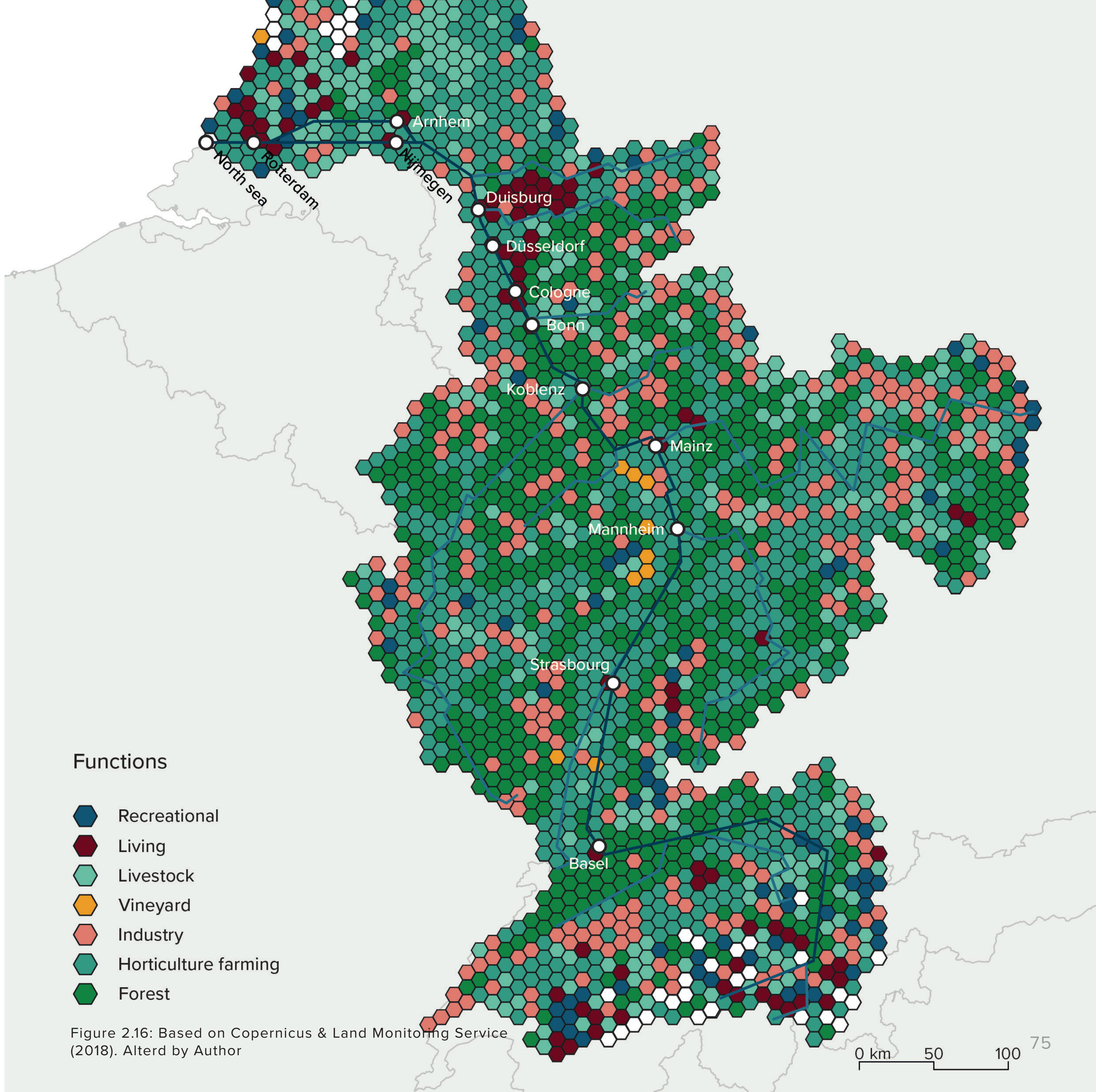


Figure 2.16: Based on Copernicus & Land Monitoring Service (2018). Alterd by Author

3.

POTENTIALS

Figure 3.1: Mannheim early 20th century unknown artist (Rhein-Museum Koblenz)

3.1 PROBLEM MAP

The problem map is a combination of different analyses found in chapter 2. This section focuses on the problems along the Rhine and determines the most problematic locations.

In the map, two extreme discharges of the river Rhine are visible. During the summer seasons, there is an increase in low discharge with extremely low flows. On the other end of the spectrum, there is also an increase in high discharge noticeable in certain moments of the year. Typically these happen during winter periods but are also possible at other times of the year.

The surrounding area of the Rhine has a large percentage of artificial surfaces. Bare rocks are located in the southern part of the Rhine catchment area. These surfaces have a high run-off, combined with low infiltration. Low infiltration causes aquifers and groundwater to be unable to recharge. The run-off running down to the river over artificial surfaces also gets more contaminated, reducing the already poor water quality of the Rhine even more.

Areas with a high or moderate vulnerability to drought have a greater chance of experiencing drought-related problems. These areas often overlap with the regions with higher susceptibility to flood. These areas experience extreme scenario's more often and are generally more vulnerable.

Narrow spaces along the streamflow leave little to no room for interventions. These areas also have no place to guide an excess of water, leaving them highly vulnerable to flooding. At the same time, there is no natural space to store water for moments of extreme drought.

Agricultural droughts can impact the food supply chain. Areas with below-average soil moisture have a greater risk of experiencing agricultural droughts. The areas close to the river have more consequences during streamflow droughts as irrigation water is hardly available and there are limited reserves.

Areas with low-productive aquifers have less water reserves. This leaves them more vulnerable when streamflow drought hits and the dependent industries on the Rhine have no natural backup.

Glaciers and perpetual snow are a big part of the streamflow during the spring season. With the melting of glaciers and the disappearance of perpetual snow, this supply to the streamflow diminishes, leading to more prolonged and severe streamflow depletion.

Salt intrusion affects the ecosystem negatively and creates a problem with the quality of drinking water.

Areas where the Rhine is narrow, tend to overlap with areas more vulnerable to droughts and floods. This can create problems as there is little room for improvement or water collection. Noticeably, areas with below-average soil moisture do not always overlap with moderate vulnerability to drought or low-productive aquifers. These areas overlap more with agricultural regions, possibly because they tend to use more groundwater, creating this problem of below-average soil moisture, as there are limited options to recharge the groundwater.

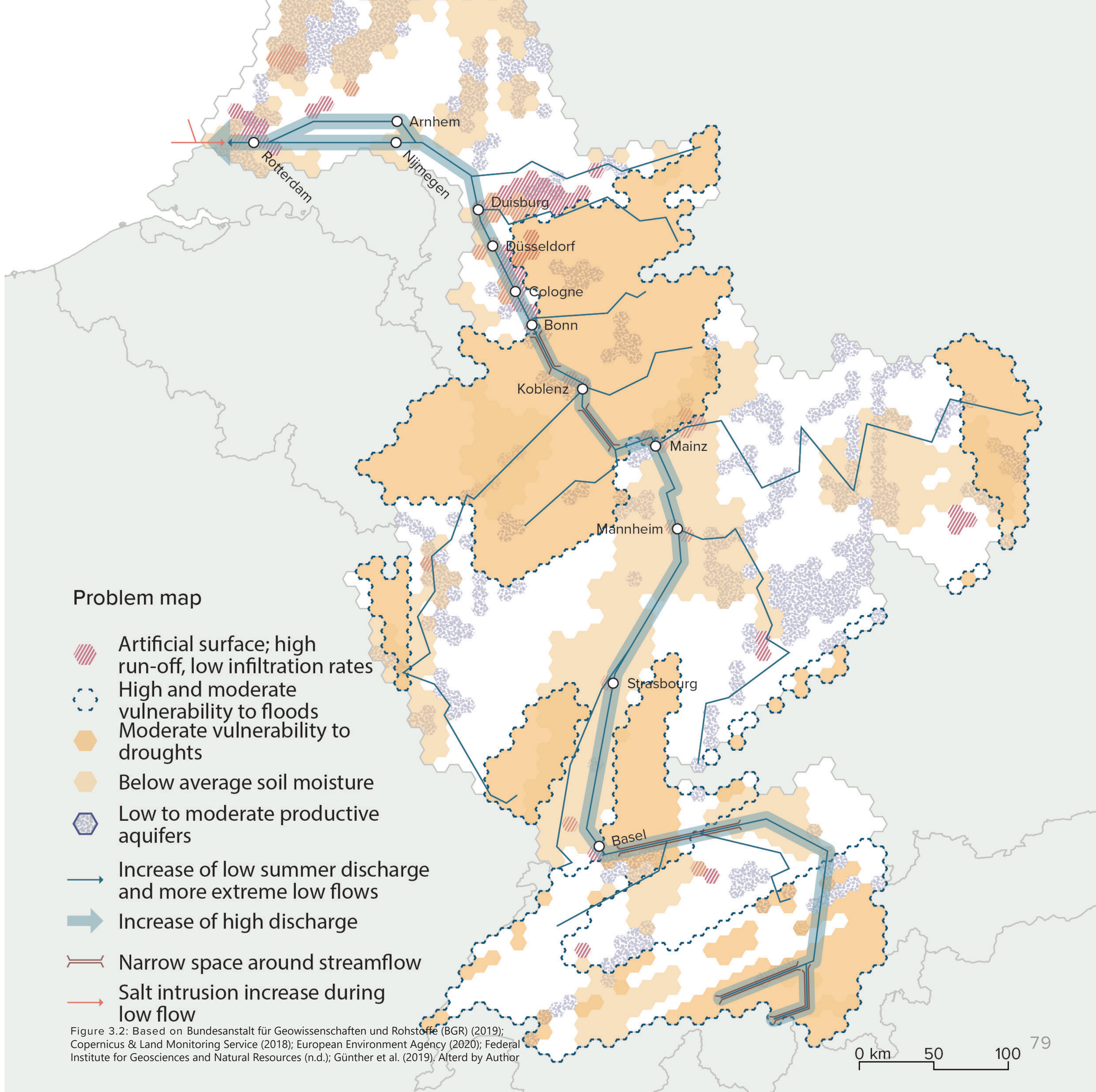


Figure 3.2: Based on Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) (2019); Copernicus & Land Monitoring Service (2018); European Environment Agency (2020); Federal Institute for Geosciences and Natural Resources (n.d.); Günther et al. (2019). Alterd by Author

3.2 OPPORTUNITIES MAP

The opportunities map is a combination of different analyses found in chapter 2. This section focuses on the space for opportunities along the Rhine to mitigate drought and implement a strategy.

One of the most significant opportunities for drought mitigation is the old water structures found in the Rhine catchment area. These once-redirected sections of the Rhine are often still visible in the landscape and have a lot of potential. Small water structures are still present and can be extended and reconnected. By reconnecting, there is a more substantial base for flood prevention, and at the same time, water can be stored for times of drought. Existing wetlands and forests are a possible basis for expansion and typically have a better soil structure for infiltration. Combining these areas with infiltration-enhancing measures, groundwater and aquifers can be recharged and used during drought.

The urban edge plays an essential role in the strategy of Every Drop Counts. The artificial areas have less space for drought prevention measures, so creating a synergy between urban and rural areas can give room to this strategy. Besides that, experiencing drought can help with raising awareness. That can help reduce water waste and give more room to implement drought-mitigating measures.

Highly productive aquifers have an opportunity to store water. This water can then act as a buffer during droughts. By implementing strategies that improve infiltration in these areas, groundwater and aquifers can recharge during wet seasons.

The plateau landscape in the Rhine catchment area is a flat space with more room to implement strategies.

Noticeable is that old water structures and highly productive aquifers overlap. Similarly, many productive aquifers are underneath land uses of wetlands and forests. These areas are potential spaces to implement infiltration-enhancing measures.

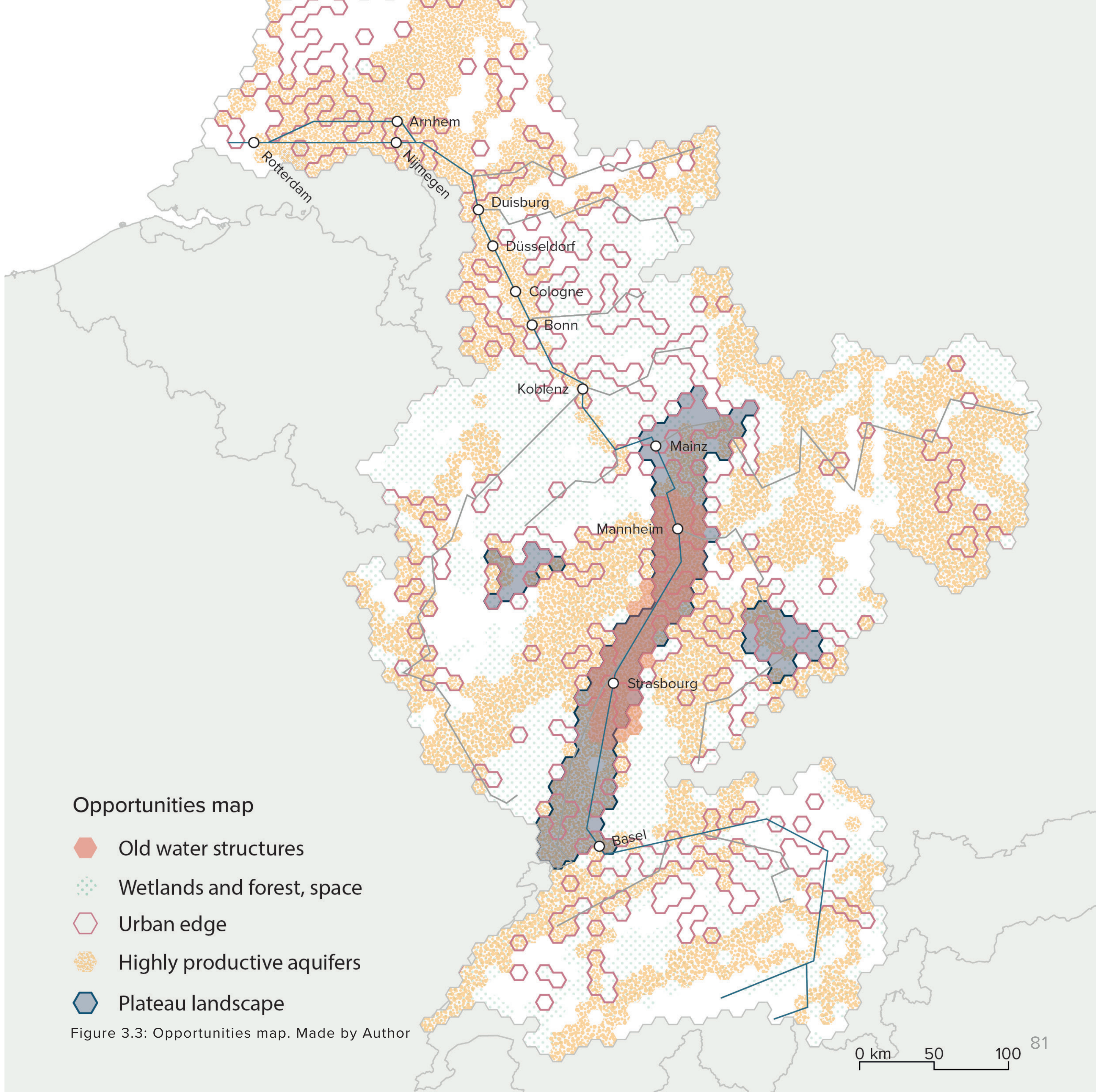


Figure 3.3: Opportunities map. Made by Author

3.3 TOWS

	Opportunities	**Threats**
	• Old oxbows and river meanders • Green or Wetland land use • Improvement of biodiversity • Connecting green and blue structures • Water retention • Flood protection measures • High discharge of river streamflow • Area where Urban and rural meet	• Climate change • Drought • Water quality depleting • Population growth • Food scarcity • Salt intrusion • Low productive aquifers • Run-off
Strenghts • Biggest inland waterway transport facilitator • Supporter of different functions • Diverse landscape and geomor pholgical structures • Diverse biodiversity	**Making use of opportunities with strengths** • Improving the existing biodiversity by connect green and blue structures • Keeping the Rhine the biggest inland waterway transport river of Europe by creating more water storages and improving infiltration of soil • By creating more flood protection measures • Using the diverse geomorphology as an advantage for different drought mitigating measures	**Preventing threats with strengths** • Large scale biodiversity to battle run-off • Mixed land use to create more diverse opportunities to prevent drought • Using the diverse geomorphology to battle drought
Weaknesses • Dependentness on the Rhine for cooling of energy production • Dependentness on the Rhine for drinkwater • Slow-onset natural hazard • Little to now coöperation between countries and institutions • Low summer discharge and extreme low flows	**Using the opportunities to minimise weaknesses** • Creating a buffer with water that is available during high discharges to reduce the dependentness of cooling for energy production • Creating stronger green and blue structures or water storage facilitities that raise awereness for drought problems	**Minimising potential pitfalls where threats and weakness meet** • Creating a green-blue network to mitigate drought and keep the Rhine functional • Create a vision for the Rhine beyond borders, focusing on the Rhine as a singular entity

Figure 3.4: Kaub gauging station (Author, 2022)

3.4 POTENTIALS

The potentials map is a conclusion map to find different potential design locations by combining the problem and opportunities map.

For the project, Every Drop Counts, two design locations are picked. These locations are picked based on a set of requirements.
For location 1, these requirements are:
- The location must be in the near vicinity of a city.
- It must have visible old water structures in the landscape.
- Horticulture and livestock functions must be present.
- There must be available space to implement drought-mitigating measures.
- There must be areas with drought problems in the locations

For location 2, these requirements are:
- The location must be in the near vicinity of a city.
- There must be industrial functions present.
- There must be horticulture and livestock functions present.
- There must be available space to implement drought-mitigating measures.
- There must be areas with drought problems in the locations
- The area has problems with water quality decline.

These criteria and the two maps gave multiple hits of areas that fit the described criteria. These locations are displayed on the map of the potential.

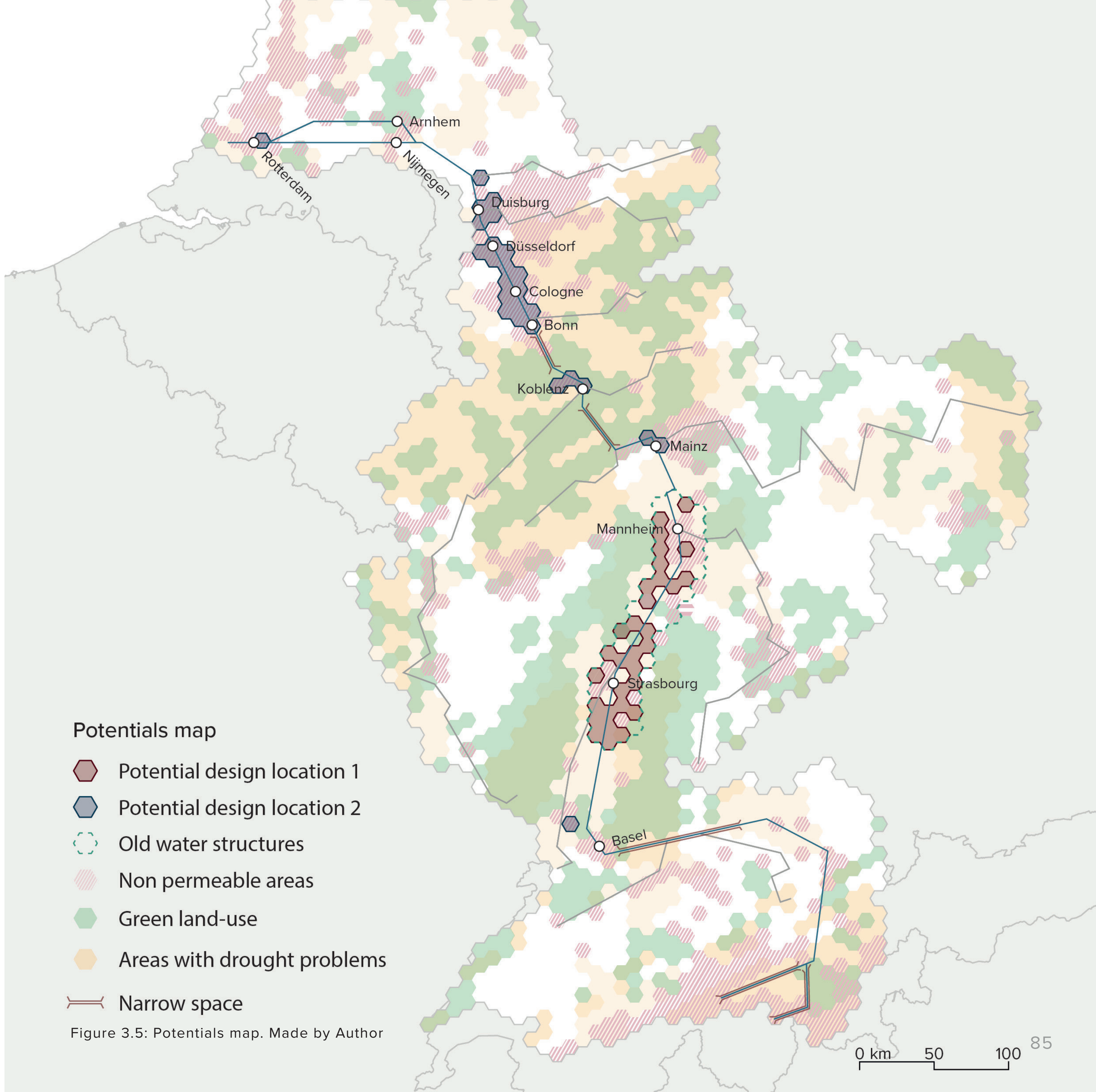


Figure 3.5: Potentials map. Made by Author

VISION & CONCEPT

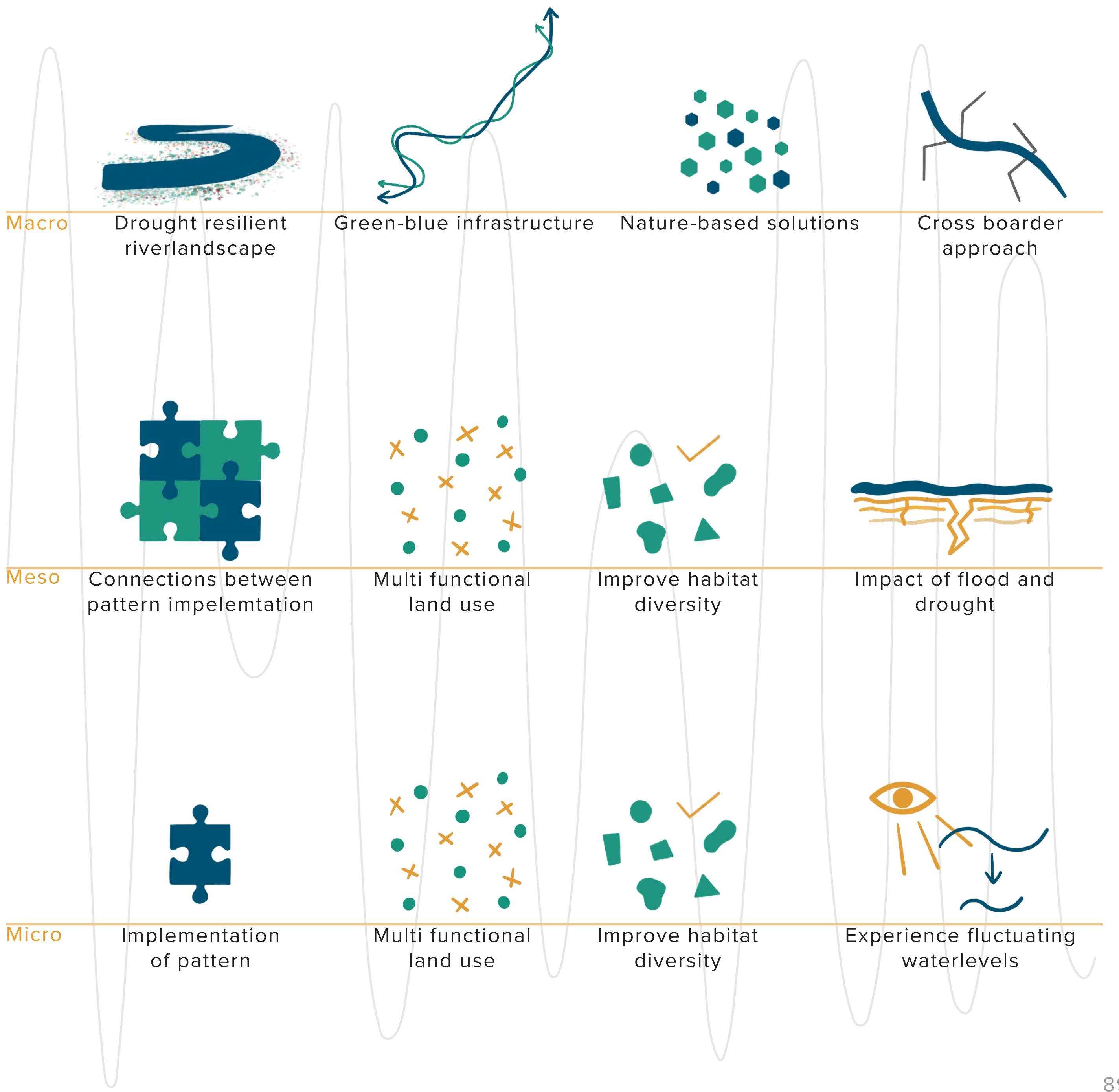
4.

Figure 4.1: Ice Drift by Heinrich Hartung III, 1919 (Rhein-Museum Koblenz)

Green-blue infrastructure approach & nature-based solutions
Nature-based solutions are actions that work with nature and its ecosystem. The solutions address issues like climate change, biodiversity loss, drought, and urbanization with a sustainable and cost-effective approach and include human well-being. When nature-based solutions are implemented individually, the focus is on single- and small-scale focused solutions. This small-scale approach can negatively impact the flow of ecosystem services on a larger scale.
Green-blue infrastructure approach revolves around the network of ecosystems and considers a cross-scale relationship to be critical. The segmentation of ecosystem services can be avoided by approaching nature-based solutions as actions that strengthen the interconnected green-blue infrastructure. The green-blue infrastructure networks can be optimized with nature-based solutions, while the nature-based solutions can be strategically prioritized.
Within this research, the combination of green-blue infrastructure networks optimized by nature-based solutions has been attempted in a multiscalar approach. The overall vision of the Rhine has a green-blue infrastructure approach. The nature-based solutions within this infrastructure will be highlighted when zooming in on different locations. Examples of this can be found in chapter 6.

Human-nature interaction
Human-nature interaction is an essential benefit for human well-being. Keniger et al. (2013) conclude in their literature review that interaction with nature can have many positive benefits for humans. Interaction with nature has positive effects on physical and psychological health. But it can also create social cohesion and is an important facility for activities that are important for the well-being of people.
Creating nature areas accessible to humans, therefore, has an important impact on human well-being. The strategy for the Rhine areas close to urbanized areas should be accessible to stimulate these positive interactions.

Drought awareness
Drought events did not have the same impact as flooding events. Because of this, drought mitigating measures are not yet implemented on a large scale and cooperation between stakeholders are yet to be established.
Severe events usually achieve awareness of environmental issues. Drought events are a slow-onset hazard, meaning that they slowly creep up and are hardly noticeable in daily life as it gradually changes over time. Implementing larger green spaces for recreation can help raise awareness. This awareness can be raised by creating a space that people can walk through that shows different experiences each season. When the extremes of flooding, the typical situation and drought periods can be experienced in a green space, differences become more noticeable, and the support for climate adaptation measures becomes greater.



Vision statement

The Rhine becomes a connected green-blue infrastructure. This infrastructure is based on nature-based solutions that form a coherent system where the green-blue infrastructure works in a cross-border approach. The new green-blue solutions add to habitat diversity or allow new habitats to develop.

On a local, near-urban scale, nature will be accessible to humans. Here the human-nature interaction is a fundamental part. The human-accessible green-blue structures will increase awareness of the impact of droughts and floods. Here people can experience the difference in water levels and the effects on nature first-hand. In cities along the Rhine, the interaction with the river will be enhanced in a nature-based approach where riverbank protection is scaled-down. The urban areas will provide more interaction with the river.

Current land uses will be reallocated. There is more room for a green-blue infrastructure along the Rhine. Agricultural land uses can incorporate multifunctional land use by being part-time available for water storage in times of need. Soil structures will be improved, and water infiltration into the soil will be enhanced. Near urban development, more space for green-blue recreational functions will be implemented. These areas will be partly water storage and provide room for recreation. Industrial zones will have optimized water use, where water taken from the Rhine will serve as much purpose as possible before being filtered again and added back to the streamflow. Along the Rhine will be more room for wetland areas and water storage to combat droughts and floods.

By having more storage capacity along the Rhine and enhancing infiltrations of soil, the water levels in the Rhine are kept more constant, leading to a more economically resilient Rhine.

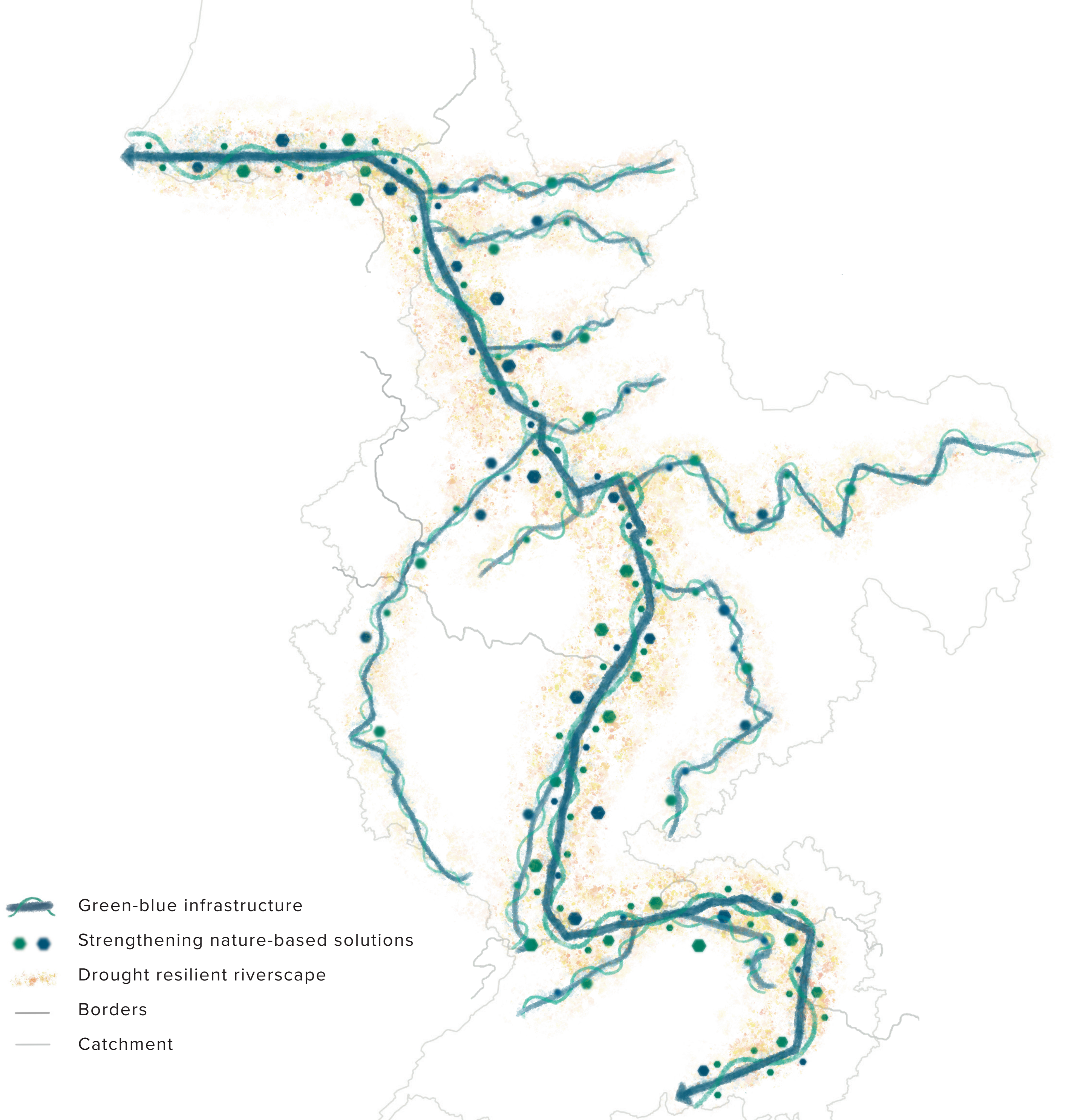


Figure 4.2: Vision map for the Rhine. Made by Author

STRATEGY

5.

Figure 5.1: Blick vom Isteiner Klotz Rheinaufwärts gegen Basel by Peter Birmann (Birmann, 1844)

5.1 INTRODUCTION INTO PATTERNS

The pattern catalogue

Patterns are flexible principles that can be adapted to various situations and locations. In this strategy, the patterns are based on the book by Alexander et al. (1977) that explores the concept of patterns. The patterns are essential guidelines that can be used to solve specific design problems in a distinct context. A pattern gives information about the crucial guidelines and where and how these design principles could be implemented. The patterns inform in which context they would be most effective.

The patterns are a design tool to distil design solutions into a set of underlying principles (patterns) that can be applied across various situations. Some patterns can be combined to enhance one another. The patterns are flexible and adaptable to the situation, creating a functional result. The patterns are a starting point for designing, giving the designer the best-suited solutions for the location. These patterns can then be tailored and combined with a site's needs.

Patterns are also used as communication tools towards all stakeholders and designers. These design solutions are made digestible for all stakeholders with a short overview of information and a clear explanation. They help stakeholders work together and ensure that everyone involved in a project works towards the same goals.

Every Drop Counts and patterns

Every Drop Counts uses a green-blue infrastructure approach. With this, patterns are cross-border applicable and aim to connect. The overall aim of the patterns for Every Drop Counts is to create an overview of design measures that can be implemented along the Rhine to mitigate drought problems. The patterns are focused on their ability to alleviate drought and flood. Because of many possibilities, these patterns contain a filtering system considering the need for infiltration or placement along the streamflow. These patterns will be implemented in a design strategy to show how they can be used.

The Pattern Catalogue is based on the European Natural Water Retention Measures catalogue from the EU Directorate General Environment. They collected different NWRM to support the green infrastructure, where the biophysical impacts of these measures are indicated. The main focus of these measures is to enhance the retention capacity of aquifers, soil, and aquatic and water-dependent ecosystems.

The patterns are divided into four categories, as used for the NWRM, namely, agriculture, forest, hydro morphology, and urban. The following pages will show an overview of all patterns in this catalogue. Then the application of the patterns will be further discussed, and the filtering of the patterns will be explained. For an extensive overview of the patterns and an in depth explanation of the use of the patterns a supplemental booklet is available, the Pattern Catalogue of Every Drop Counts.

5.2 PATTERN OVERVIEW

Urban

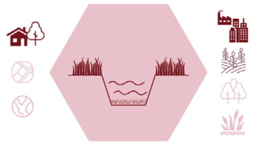
Swales

Swales are vegetated channels that store or transport surface water, reducing run-off rates. They can be used to promote infiltration. Swales can improve water quality, and can provide biodiversity. They can be used in a wide range of situations. There are three types: standard conveyance, enhanced dry, and wet swale.

Rainwater harvesting

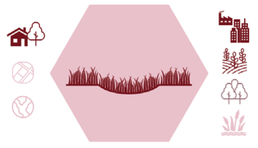
Rainwater harvesting is collecting and storing rainwater using water butts or larger tanks. Water butts are primarily for small-scale use in households, while tanks can manage stormwater volumes. However, rainwater harvesting is limited during wet periods and should be considered part of a sustainable water management system in combination with other measures.

Infiltration trenches



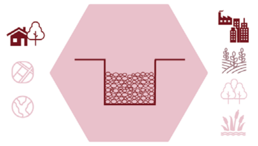
Infiltration trenches are shallow channels filled with rubble or stone. These trenches let water infiltrate into the soil. Infiltration trenches help reduce run-off, recharge groundwater and improve water quality.

Filter strips



Filter strips are gently sloping strips that treat run-off through vegetative filtering. They intercept sedimentation and let water infiltrate. Filter strips can be used as a pre-treatment technique in small drainage areas. They can serve as buffers between conflicting land uses and help with groundwater recharge.

Soakaways

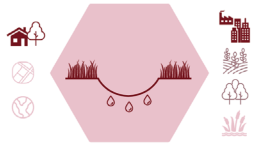


Soakaways are underground storage that store and allow surface water to soak into the ground. They provide stormwater treatment, recharge groundwater, and have the potential to mitigate low river flows. Soakaways are easy to integrate into sites and do not take up land. They do not have any additional benefits for biodiversity.

Rain gardens

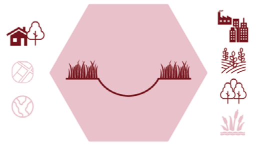
Rain gardens capture and infiltrate precipitation and stormwater run-off. They use different components in the design to increase infiltration and to store run-off. These types of gardens have a flexible layout and should enhance landscaping features.

Infiltration basins



Infiltration basins keep run-off from settling on impermeable surfaces and allow water infiltration into soils and groundwater. They improve water quality and flow control. These basins are dry and only function as infiltration basins during large amounts of precipitation.

Detention basins

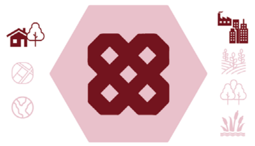


Detention basins are vegetated impressions in the landscape that holds run-off. They allow pollutants and sediments to settle. Detention basins do not allow infiltration, and water is drained into nearby water structures.

Retention ponds

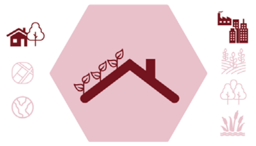
Retention ponds are designed to hold excess run-off and release this water slowly to prevent flooding. They can improve water quality and are shallow zones for ecology. Retention ponds have ecological benefits and can be incorporated into public open spaces.

Permeable paving



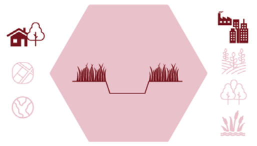
Permeable paving allows rainwater to infiltrate through the surface of paved areas. There are two types: porous pavements and permeable pavements. It can be used in most ground conditions and is commonly used on low-traffic roads and car parks. All kinds of permeable paving provide rainfall infiltration and potentially store run-off from surrounding areas.

Green roofs



Green roofs cover a building's roof with vegetation and a drainage layer. There are two types: extensive, which covers the entire roof with low-maintenance vegetation, and intensive, which requires more maintenance and can include planters, trees, and water features. Green roofs intercept rainfall and reduce flow rates, providing a sustainable drainage system.

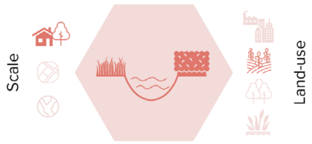
Channels and rills



Channels and rills are shallow channels with open surface water that capture and slow run-off. They can collect and store debris, treat pollution, and guide water downstream. They can be designed in different varieties, and the planting can improve water quality.

Agriculture

Buffer strips and hedges



Buffer strips provide effective water infiltration, and they slow surface run-off. Permanent vegetation along buffer strips promotes the natural retention of water. By implementing hedges alongside buffer strips, soil erosion can be reduced and slow surface run-off, especially along sloped areas.

No till agriculture

Tillage, the mechanical modification of soil, can disturb soil structure and increase soil erosion problems. By altering soil structures, the retention capacity can be decreased. By implementing no till agriculture, water infiltration into the soil will increase and reduce soil erosion.

Reduced stocking density

Livestock can have a severely destructive impact on the soil structure. By reducing the density of livestock, the negative effects on the soil are reduced. Water infiltration into the soil gets less impacted, leading to better groundwater recharge and less flood risk.

Intercropping

Intercropping is the practice of growing two or more crops next to each other. By intercropping, greater yield can be produced, and land can be more productively utilised. By using a combination of deep-rooted and shallow-rooted crops, infiltration rates of soil can be improved. By using intercropping, space can be created for other water retention measures.

Traditional terracing

Traditional terracing is implemented along slopes. These platforms, created in sloped areas, can be sustained by stone walls and support farming. The structure of terracing can reduce soil erosion and slow down surface run-off. Because of the horizontal layout, infiltration is also improved.

Meadows and pastures

Meadows and pastures improve soils with their roots and make good conditions for the uptake and storage of water. They can function as temporary storage during a flood. They can add increased water retention and recharge groundwater.

Mulching

Mulching is the application of adding material to the surface of the existing soil. Preferably the mulch is an organic material. Mulching can improve the capacity of the soil to store water.

Green cover

Green cover is the planting of crops in the late summer or autumn. Green cover protects the soil against erosion. Green cover can also improve soil structures and improve the infiltration of soil.

Low till agriculture

Tillage, the mechanical modification of soil, can disturb soil structure and increase soil erosion problems. By implementing low till agriculture, water movement slows and can lead to more significant infiltration. By altering soil structures, the retention capacity can be decreased.

Controlled traffic farming

Controlled traffic farming is the principle of reducing the traffic on farmable land to a limited area to decrease heavy traffic's impact on the soil structure. By not going over arable land with heavy traffic, soil infiltration rates stay optimal.

Crop rotation

By practising crop rotation, different crops will be growing in different seasons. Other crops can improve soil structure. The rotation between different root structures can reduce erosion and increase infiltration capacity.

Early sowing

By implementing early sowing, usually up to six weeks earlier than the typical sowing season, winter crops can root and create a more robust green cover for the winter. This green cover protects the soil against erosion. It can also improve soil structures and infiltration rates. Early sowing can also help with the impact of drought during summer, as plants are already rooted.

Strip cropping along contours

Strip cropping is the practice of using closely sown crops to create natural dams for water to improve soil strength and stop erosion. This practice is used on steep or long slopes.

Forest

Water sensitive driving

'Water sensitive' driving is the avoidance of off-road driving and through wet areas. By implementing these driving styles, soil structures will not damage. The measure also avoids the creation of different flow paths that could disrupt water cycles. The benefits of water-sensitive driving are visible on a small scale but can be noticed on larger spatial scales.

Trees in urban areas

Urban trees provide microclimate regulation and hydrological benefits. They enhance infiltration capacity and rainfall storage. They also serve as biodiversity refuges and intercept precipitation, reducing the amount of precipitation sewer, and water infrastructure have to process.

Targeted planting for catching precipitation

The afforestation of reservoir catchments extends the lifespan of the reservoir and improves water quality. The roots control soil erosion and increase water infiltration rates into the soil. The forest in reservoir catchments should be managed naturally to prevent water quality from depleting.

Sediment capture ponds

Sediment capture ponds are temporary engineered ponds that slow down run-off and capture the suspended materials of the run-off. They ensure that streamflow keeps water streams sediment free and improves the water quality. When properly maintained, sediment capture ponds can maintain their efficiency.

Urban forest parks

Urban forest parks provide various ecosystem and hydrology-related benefits. They enhance air quality, biodiversity, and recreation and mitigate climate change while improving local microclimates. Forest soil has a higher infiltration capacity than other urban land covers, considerably impacting aquifer recharge.

Peak flow control structures

Peak flow control structures are ponds designed to reduce water flow velocity in forest ditch networks, contributing to sediment control and reducing flood peaks. While they have a temporary function due to sediment accumulation, maintenance can be done by removing sediment to maintain efficiency.

Maintenance of forest cover in headwater areas

Maintenance of forest cover in headwater areas is the management and conservation of forested lands in the upper regions of a river basin. By implementing forest in headwater areas, the soil has a better infiltration capacity and can help regulate water availability. Forest cover in headwater areas can also reduce the risk of floods and droughts downstream.

Land-use conversion

Land use conversion as a water retention measure is the implementation of afforestation on a large scale. Afforestation can intensify the water cycle and have a positive effect downstream. But it can cause water shortages locally due to the tree's water needs and higher evaporation rates.

Appropriate design of roads and stream crossings

The design and materials used in the design of roads and stream crossings can strongly impact the erosion risk and water quality of rivers. Poorly designed stream crossings can cause sediment accumulation and change flow patterns.

Overland flow areas

Overland flow areas are designed to minimise the impact on water quality by removing sediment from ditch maintenance, road building, or harvesting. They are created by building a semi-permeable dam and ditches to divert water. The water slows down, depositing sediment before reaching the receiving water body.

Forest riparian buffers

Forest riparian buffers increase the infiltration of water into groundwater and aquifers. When implemented along open water, they help slow down run-off, store water and decrease sediment inputs into the open water. The roots of the trees help with erosion control and increase infiltration rates.

Continuous cover forestry

Continuous cover forestry combines a range of forest management practices. The main principle is the protection of the soil and the creation of a continuous cover. This strategy includes a natural forest hydrological cycle with beneficial hydrological effects. Continuous cover forestry also reduces the impact of run-off.

Coarse woody debris

Coarse woody debris is the placement of artificial or naturally occurring woody debris into streamflows. Coarse woody debris in streams has ecological and hydrological benefits. It can slow water flow, reduce flood peaks, facilitate sediment accumulation and improve aquatic biodiversity by retaining food and providing additional habitat.

Afforestation of reservoir catchments

The afforestation of reservoir catchments extends the lifespan of the reservoir and improves water quality. The roots control soil erosion and increase water infiltration rates into the soil. The forest in reservoir catchments should be managed as naturally as possible to prevent water quality from depleting.

Hydro morphology

Wetland restoration and management

Wetlands can contribute to flooding prevention, water quality improvement, store water and enhance biodiversity. Wetlands provide water retention, enhance biodiversity and can improve water quality. Wetlands can be restored on a large scale or implemented as a small-scale measure.

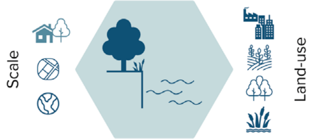
Restoration of natural infiltration to groundwater

Groundwater is a vital water resource for human activities, but landscape modifications have reduced the infiltration capacity of many European soils. Restoring the natural infiltration enhances the quality and availability of water, lowers run-off on land and improves groundwater aquifers.

Reconnection of oxbow lakes and similar features

An oxbow lake is a river meander that has been cut off from the main river to straighten the river flow. Reconnecting it to the river involves removing land between the two water bodies, which improves the river's overall functioning by restoring river flow, more potential for infiltration and enhancing water retention during floods.

Natural bank stabilisation



Riverbanks can be natural or artificial. Artificial riverbanks often have adverse effects like erosion, increased water flow and decreased biodiversity. Renaturation of riverbanks involves restoring ecological aspects to stabilise banks and allow rivers to flow more freely. Renaturing can reverse damages done to the river structure.

Elimination of riverbank protection

Removing riverbank protection enhances the connection of the river. When removed, it can diversify flows and habitats and lessen floods in mainstreams. The elimination of riverbank protection is a prerequisite for many other measures.

Streambed re-naturalization

Streambeds have been artificially reconstructed with concrete or large stones, reducing fauna habitat and vegetation diversity. Re-naturalising streambeds involves removing and replacing concrete with vegetation structures to restore biodiversity and stabilise banks using plants. Re-naturalisation also improves the infiltration of water into the soil.

Restoration and reconnection of seasonal streams

Seasonal streams are rivers that dry up during dry periods in the year but are essential for supporting biodiversity. They provide ecosystem services such as flood control and irrigation. Restoring and reconnecting seasonal streams can improve the overall functioning of the river by altering flows, improving infiltration and improving water retention during floods.

Re-naturalization of polder areas

A polder is a piece of land surrounded by dikes with its own hydrological system. The re-naturalisation of polder areas involves providing more water storage and increasing biodiversity.

Lake restoration

Lakes are water retention facilities with multiple uses, including flood control and water storage, to provide water for different functions. They also provide habitats for many species. Priority to agricultural services and lack of maintenance have led to siltation or drainage of lakes. Lake restoration aims to enhance old structures and functions where drainage once occurred.

Detention basins and ponds

Detention basins and ponds are designed to store surface run-off. When soil conditions are good, the water can infiltrate into the ground. During dry seasons detention basins are dry and store water during periods of precipitation. Ponds contain water during dry periods.

Riverbed material restoration

Re-naturalising involves restoring the natural structure of the riverbed. Riverbed material is sediment eroded upstream that is deposited on the river floor. With coarse sediment, the riverbed can be levelled. The main objective of riverbed material restoration is erosion control.

Removal of dams and other longitudinal barriers

Dams and other barriers disrupt sediment flow and disturb fauna in rivers. Removing dams and other barriers involves destroying obstacles and restoring the river profile. When this is implemented, ecological and sedimentary continuity needs to be considered.

Re-meandering

A river meander is a U-form that slows water velocity. Many rivers in Europe have been straightened and channelised for various reasons. River re-meandering creates new flow structures, gives more space for water, and improves sedimentation and biodiversity. By creating new meandering courses, new habitats for various plant and animal species can be provided.

Floodplain restoration and management

Floodplains are designed to retain flood and rainwater. However, human activities like urbanisation and land drainage have separated floodplains from the river, losing their retention capacity and ecosystem functions. Restoring floodplains requires removing sediment, modifying channels, creating wetlands and lakes and afforestation.

5.3 CHOICE OF PATTERN

Choice of pattern
As mentioned, a filtering system is created to implement the patterns in a design location. In figure 5.2, the elaborated pattern set-up is shown. Here the information used in the patterns is displayed. In figure 5.3, the filtering of the patterns is explained in a diagram.

The patterns find their origin in the Natural Water Retention Measures. This set from the EU Directorate General Environment gives three different types of information, namely impacts, benefits, and applicability. For the patterns, this information has been transformed into different outputs. First, the physical impacts will be elaborated. The physical impacts are one of the rings on the hexagonal diagram on the patterns. It contains information on the infiltration capacity, aquifer recharge, water storage, run-off, pollutant reduction, and improvement of the soils that each pattern can provide. These physical impacts have been chosen based on their capability to mitigate drought.
The second is changes in the environment. The changes in the environment are derived from the physical impacts with some input from natural water retention measures that were not used before. These changes entail:
- Flood prevention, how much does this pattern help with the prevention of flooding?
- Range, how far does the impact of this pattern reach? This can be local, regional or an impact on the whole streamflow of the Rhine.
- Drought prevention, how much does this pattern help with the prevention of drought?
- Mitigation, can this pattern reduce run-off and the pollution caused by this?
- Biodiversity, does this pattern help with improving biodiversity?
- Sponge working, does this pattern create a soil that can handle more water recharge?

A system to filter the patterns has been thought out to find out what patterns are best applicable to each location. The patterns have been extensively tested in an excel file. For the patterns, the sequence is not really of matter, but for the sake of this thesis, the following order is used. The choices are based on the design area.

The first choice consists of the geomorphology of the chosen area. From the analyses, one of the eight different typologies can be determined.

The next step will be determining if the design location is on the river's main branch or along a tributary.

The third choice is the general area of the design location. Is this in the delta, middle or headwater of the catchment area?

The fourth step is determining the primary land use. This choice is also found in the analysis and can be determined from the analysis.

The fifth step is whether biodiversity improvement is needed in the specific area. This is to be judged per design location.

The sixth and final step is the scale of the design. Small-scale designs are under 1 km2, medium scale 1 to 25 km2, and large-scale anything above.

When following these steps, a set of patterns will be determined. These can then be implemented into the design location and improve the drought problems.

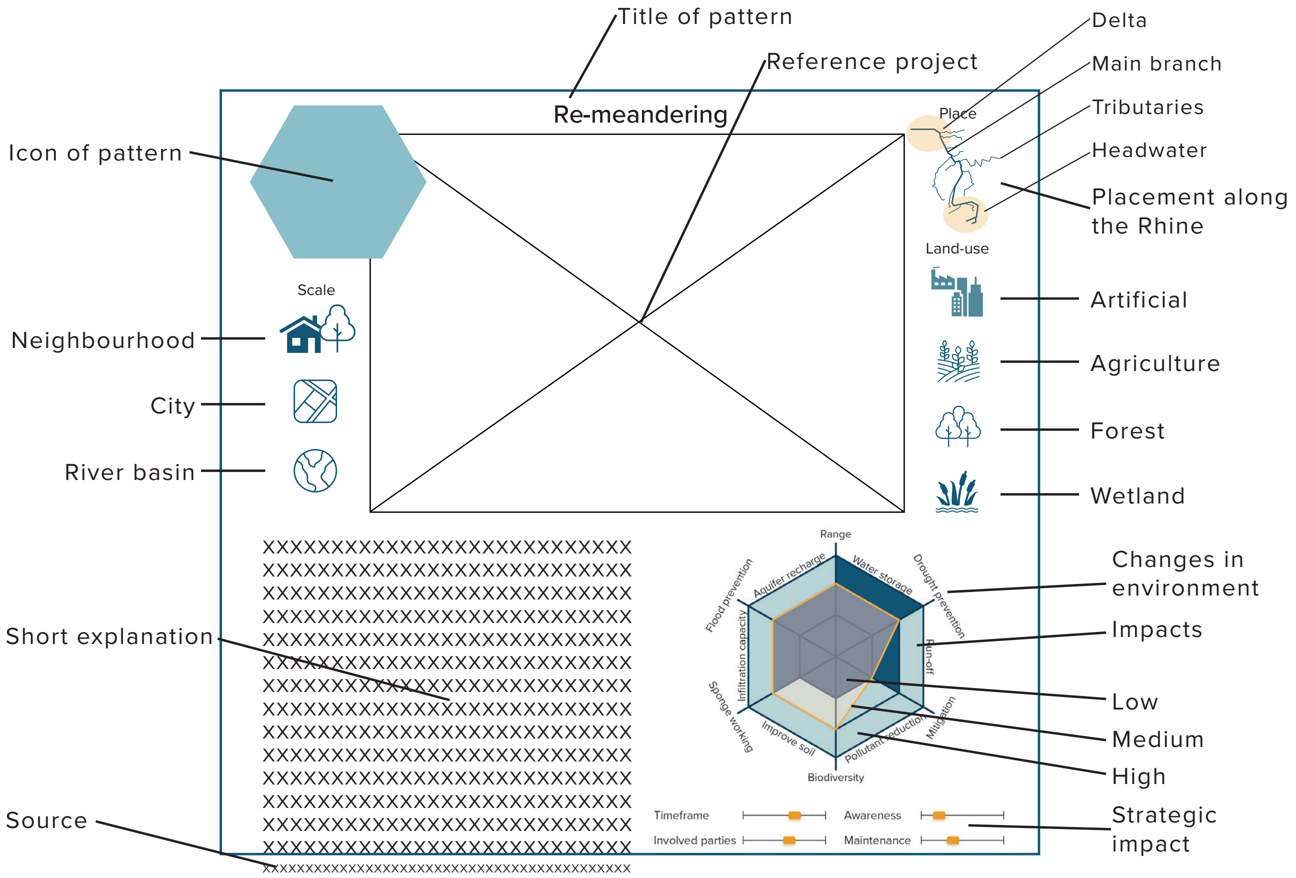


Figure 5.2: WElaborate pattern setup. Made by Author

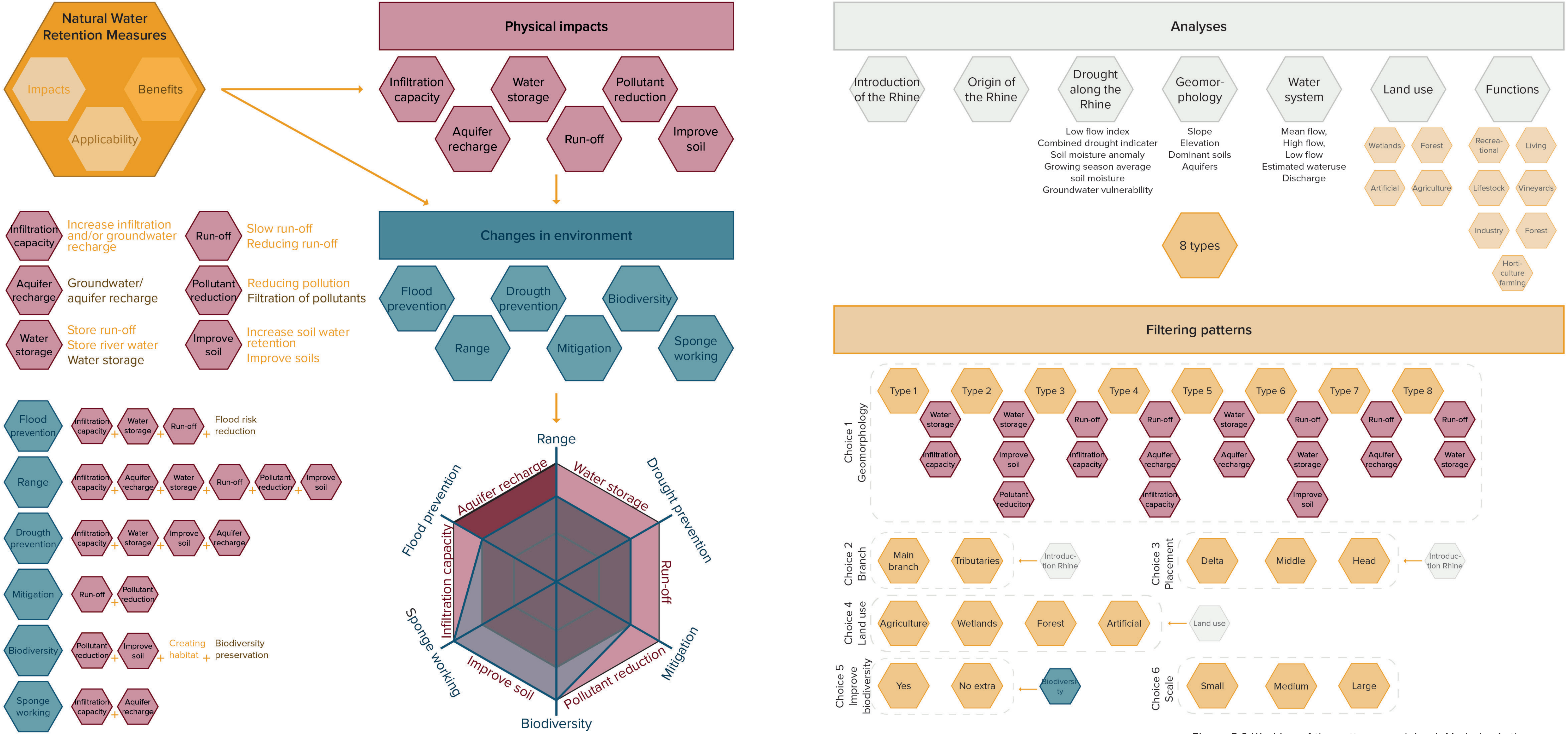


Figure 5.3 Working of the patterns explained. Made by Author

DESIGN

6.

Figure 6.1: Schiffe bei Mainz by Philipp Zeltner, 1865 (Rhein-Museum Koblenz)

In this chapter, the green-blue infrastructure approach and nature-based solutions are translated to a multiscalar design. The goal of the design is to test the capabilities of the pattern catalogue. By choosing two different design locations that fit different criteria, the filtering for patterns can be tested and refined. The design helps to clarify if the filtering system works or if gaps are found. It is also an excellent way to see if the patterns are easily implementable or need further information. The designs in this chapter are the final product of different tries and readjustments of the pattern catalogue. The designs show that it is possible to design with the help of the pattern catalogue. With this catalogue, the design strategies can then be assessed on their capabilities of mitigating drought.

After the conclusion of the analyses, where the analyses were combined into the potentials map, two design locations are chosen to test the design. These locations are compatible with the criteria set in Chapter 3.4.
The first location is just south of Mannheim. Here, many old water structures are found in the landscape. And there is a wide variety of functions. The second location chosen is Mainz. This location was chosen based on the amount of available space. Many areas had available space, but Mainz had more options to work with.

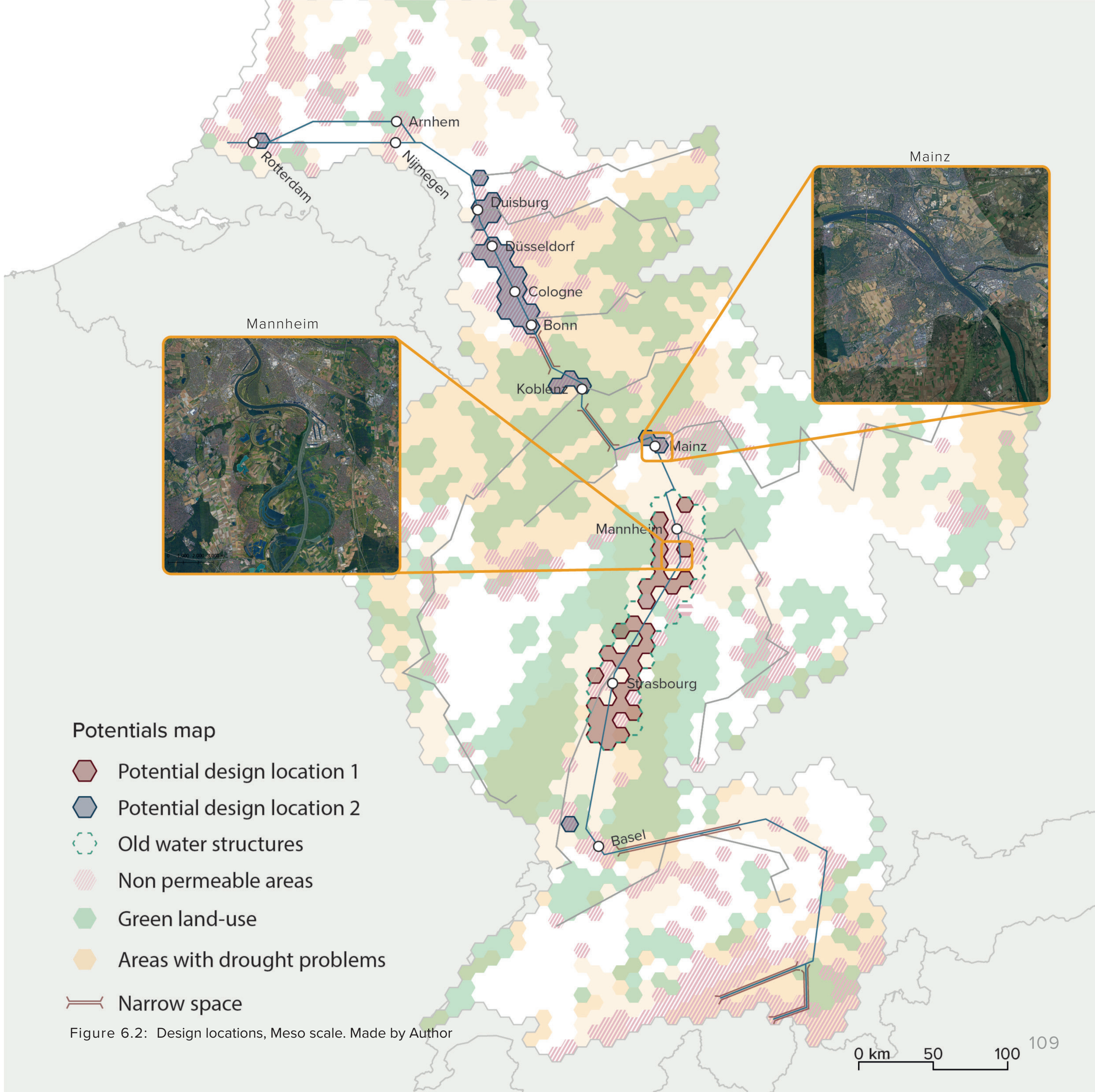


Figure 6.2: Design locations, Meso scale. Made by Author

6.1 MANNHEIM MESO DESIGN

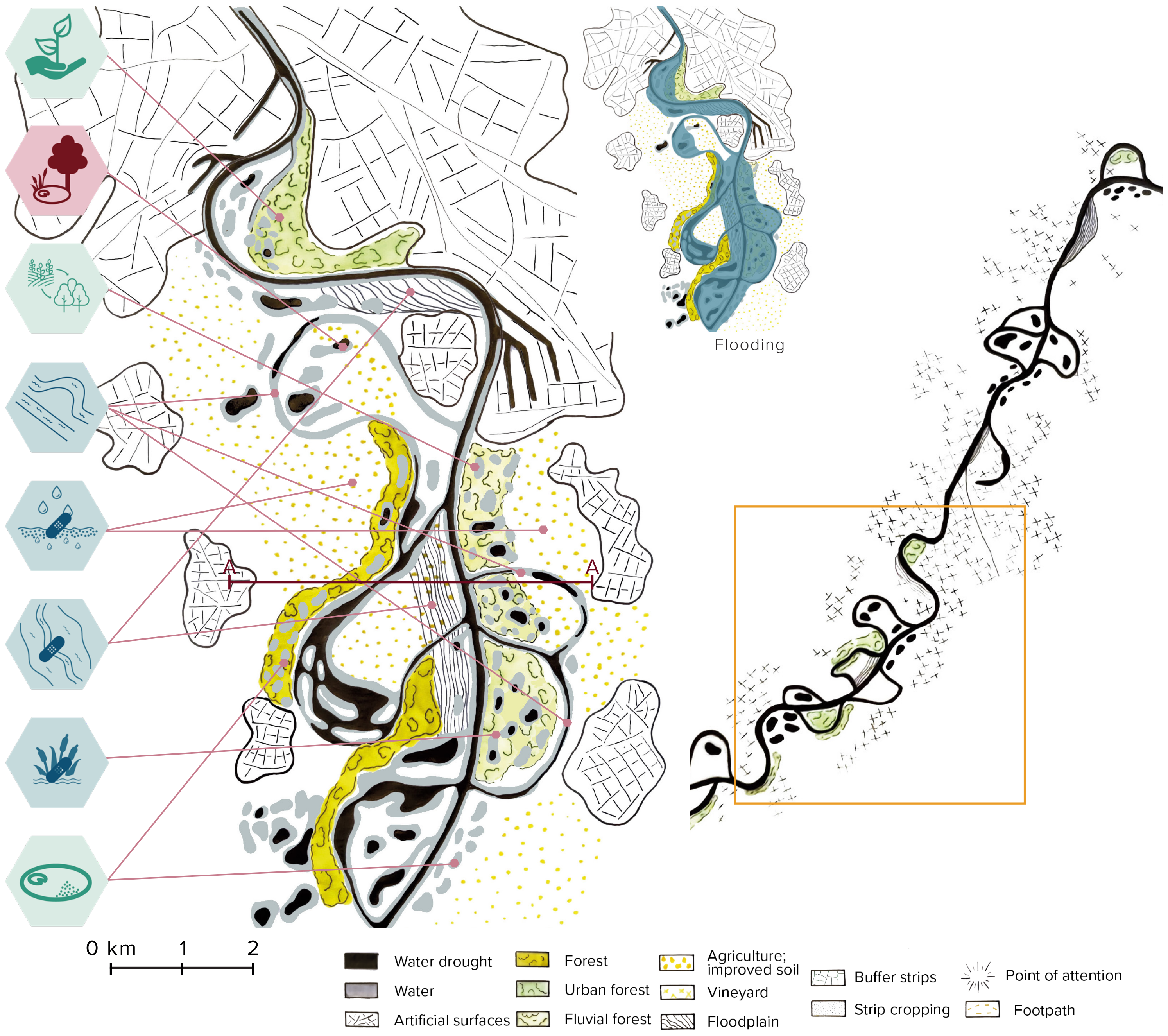


Figure 6.3: Design of Mannheim, meso scale and zoom in of vision. Made by Author

The location near Mannheim is characterized by agriculture. Villages surround the flat river landscape. Some lakes and fluvial forests characterize the nature of this area. The artificial land use of Mannheim starts here with a port area and industrial functions. Making this part of the Rhine important for the transport of goods.

For this location, the following patterns were available after filtering. For this location, all different land uses were available: **Afforestation of reservoir catchments,** Appropriate design of roads and stream crossings, Elimination of riverbank protection, **Floodplain restoration and management,** Lake restoration, **Land use conversion,** Overland flow areas, Reconnection of oxbow lakes and similar features, **Re-meandering, Restoration of natural infiltration to groundwater, Retention ponds,** Riverbed material restoration, **Sediment capture ponds,** Urban forest parks, and **Wetland restoration and management.**

The analyses for this location showed many old water structures. These water structures were used to create a basis for the new water structure of the Rhine. The idea behind the new **meanders** of the Rhine is a principle where they are connected but have a slight height difference on the spot where the Rhine connects with these meanders. This way, water gets stored for extended periods in the meander and functions more during drought. The meanders are also mainly the borders for flooding areas. The meanders chosen in this design are between the radical approach of re-meandering all old water structures and creating a minimal input plan. The structures that have been re-meanders have the most potential and still have existing parts of water bodies that could be reconnected in this design proposal.

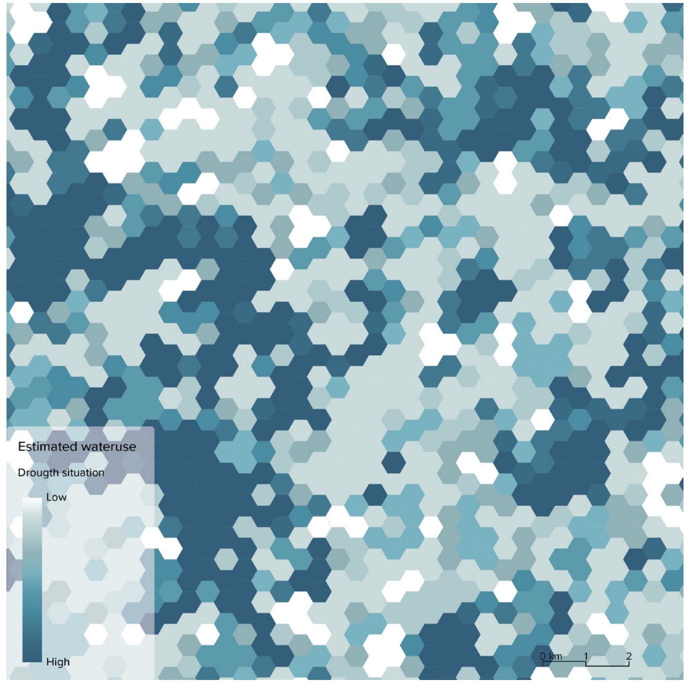


Figure 6.4: Estimated wateruse during current drought situations. Made by Author

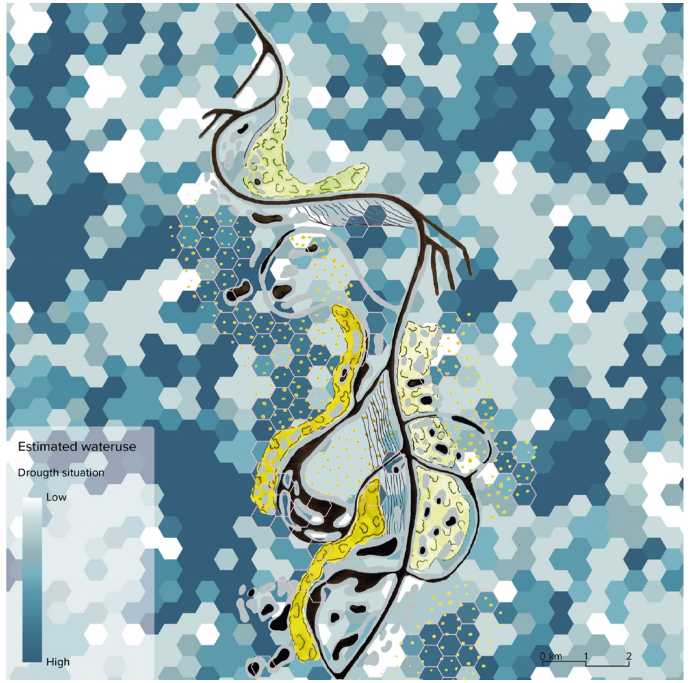


Figure 6.5: Estimated wateruse after design implementation, during drought situation. Made by Author

In the meanders, often, **wetland restoration** has been implemented. Wetland restoration can be combined with **afforestation**. By implementing these two together, **less evapo(transpi)ration** will occur, leaving more water available in times of drought. In the design, combining wetland restoration and afforestation has not been practised in every area, as creating a wide range **of biodiverse habitats** is also one of the aims of this design. Creating different types of wetlands can **improve habitat diversity**.

Besides, wetland restoration along the Rhine spots with **floodplain restoration** has been implemented. Floodplain restoration has been combined with **agricultural practices**. To ensure that the land stays viable for agriculture, these floodplains have been equipped with **sediment capture ponds**.

The overall aim of this area is to **restore the natural infiltration to groundwater**. This area has highly productive aquifers, and with better natural infiltration, these **aquifers** have time to **recharge** in wet periods to act as drought-mitigating measures during streamflow drought. Along the area, **retention ponds** have been implemented to create more water storage options to create a buffer during periods of drought.

In the vision, the green-blue infrastructure is applied on a larger scale around the meso location. The different implementations of the patterns support this infrastructure. Along the area, multiple re-meanders have been envisioned. Besides that, new places for floodplains and wetlands have been appointed. This strategy is in combination with afforestation, creating green patches along the blue structure. This way, the blue structure will be supported by diverse habitats and strengthen the overall infrastructure.

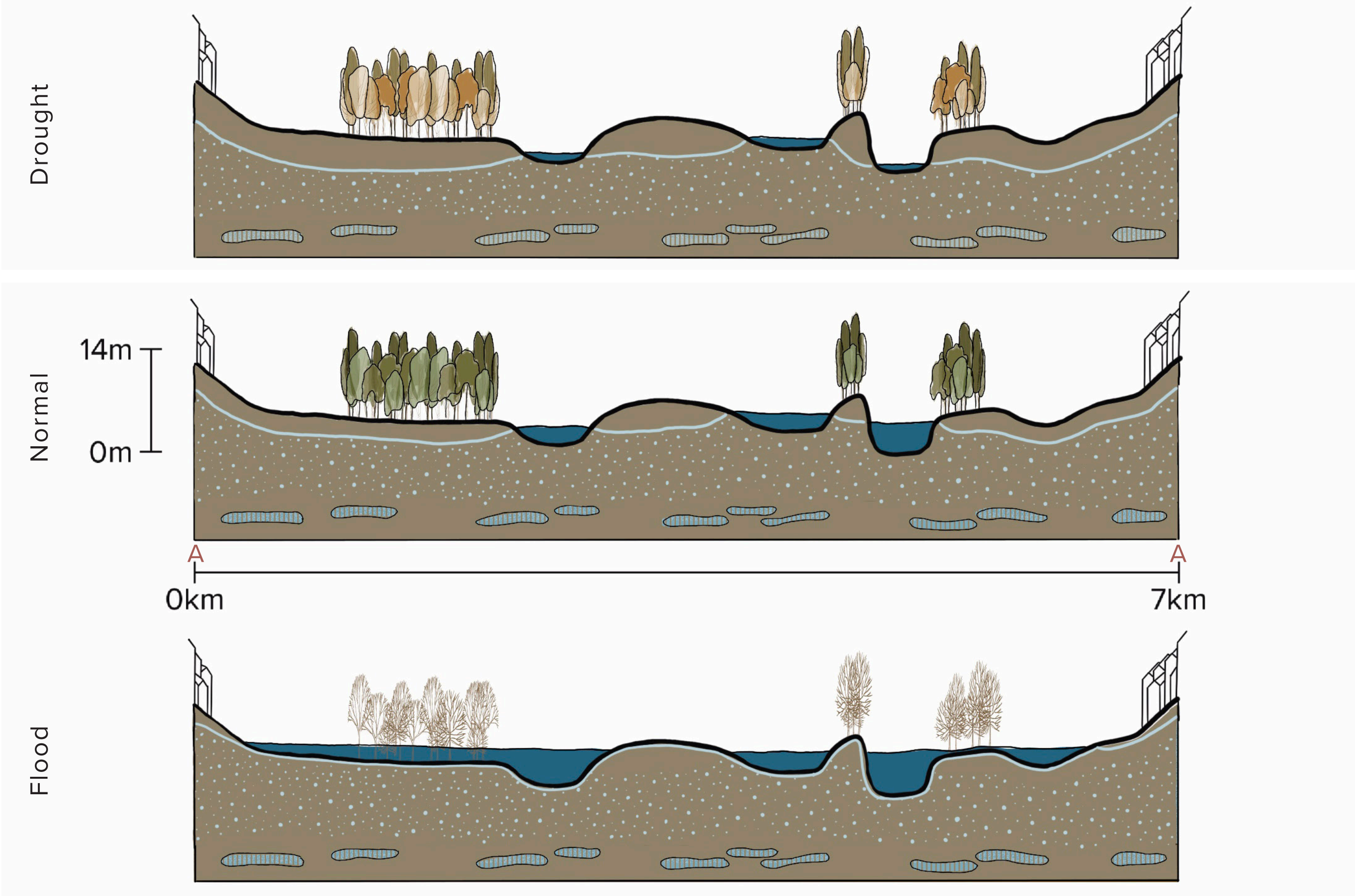


Figure 6.6: Sections of the Rhine and surrounding, Mannheim. Made by Author

Drought leaves the river with a low water level. This leaves ecosystems dry and creates problems for inland water transport and industries. With this design, some of the re-meandered rivers are close to the functions that have high water usage in times of drought. During flooding, water can infiltrate near the high water use areas and create a buffer. By implementing these strategies near the high water use areas, the water usage from the river can be reduced.

The differences between groundwater and surface water levels can be seen in the sections (figure 6.6). The section is a vertically exaggerated section to show the difference over the cross-section of the Rhine. Where the towns are located, the landscape tends to be higher. In the valley of the river, there is room for flooding. During drought, the aquifers are depleted to combat the drought problems.

6.2 MANNHEIM MICRO DESIGN

To determine the design location for the small-scale design, different analyses have been combined to create an insight into suitable design locations. An area that can show many different pattern implementations would be most suitable for these locations. This led to the creation of a grid that counted the number of different functions (represented by the yellow colours). The spots with the most diverse functions are then combined with the different types of aquifers (portrayed by the textures). By combining these two different analyses (red and green outlines), selected areas that are most diverse from these two locations were picked to design.

Figure 6.7: Location determination for micro scale Mannheim. Made by Author -->

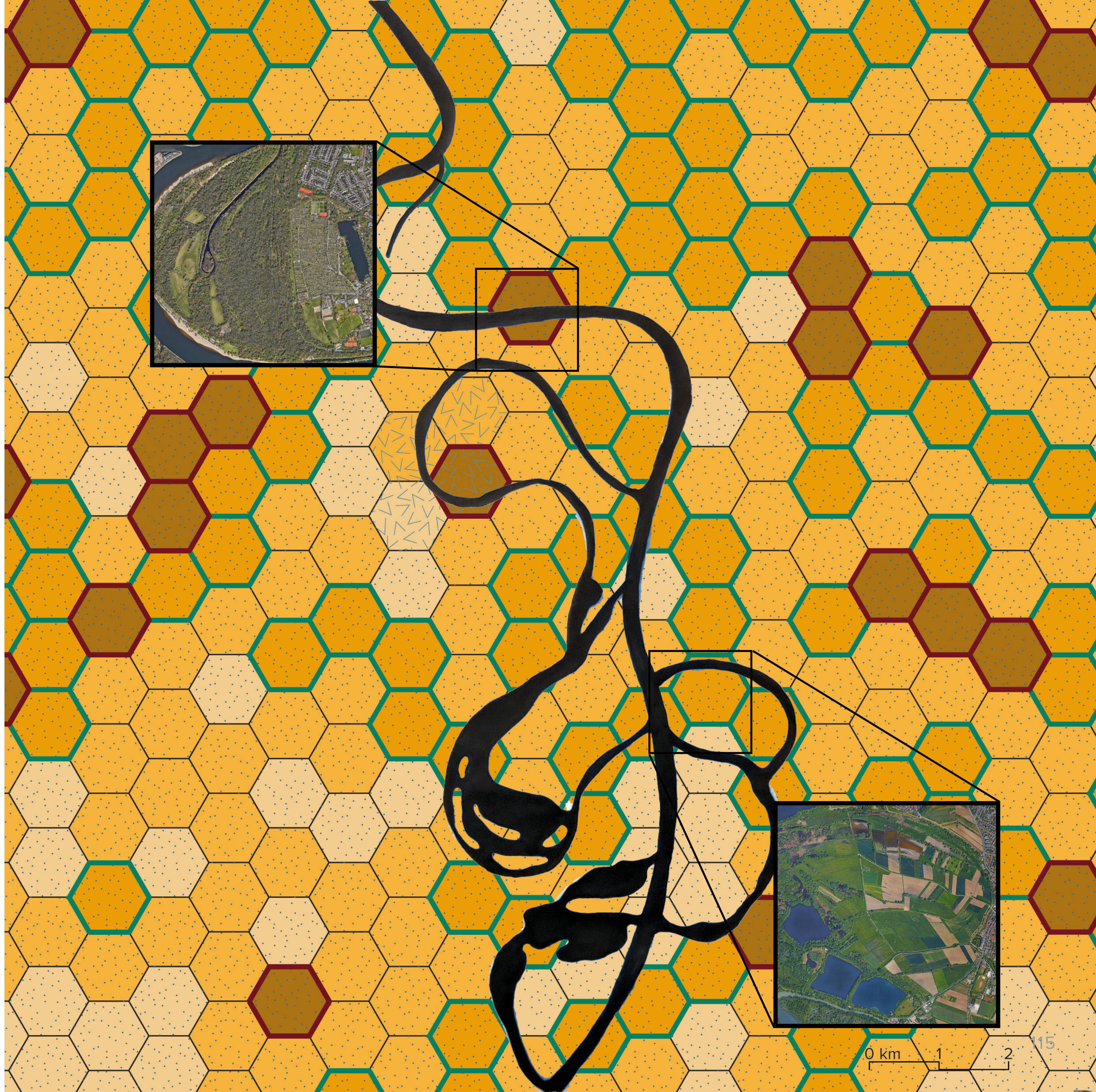


Figure 6.8: Design of Mannheim, micro scale. Made by Author

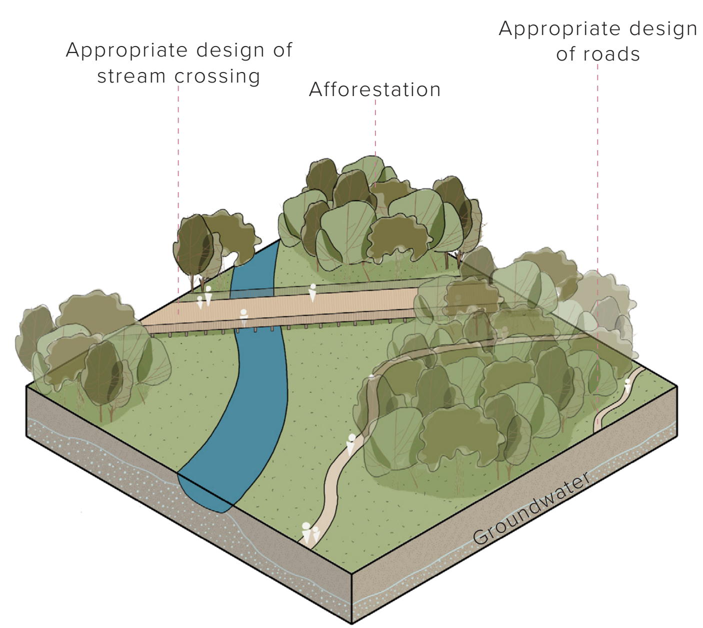


Figure 6.9: Axonometric view of the design location. Made by Author

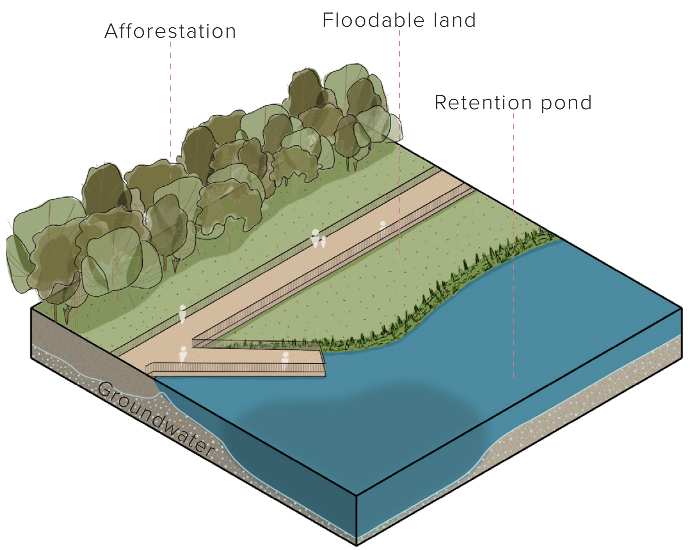


Figure 6.10: Axonometric view of the design location. Made by Author

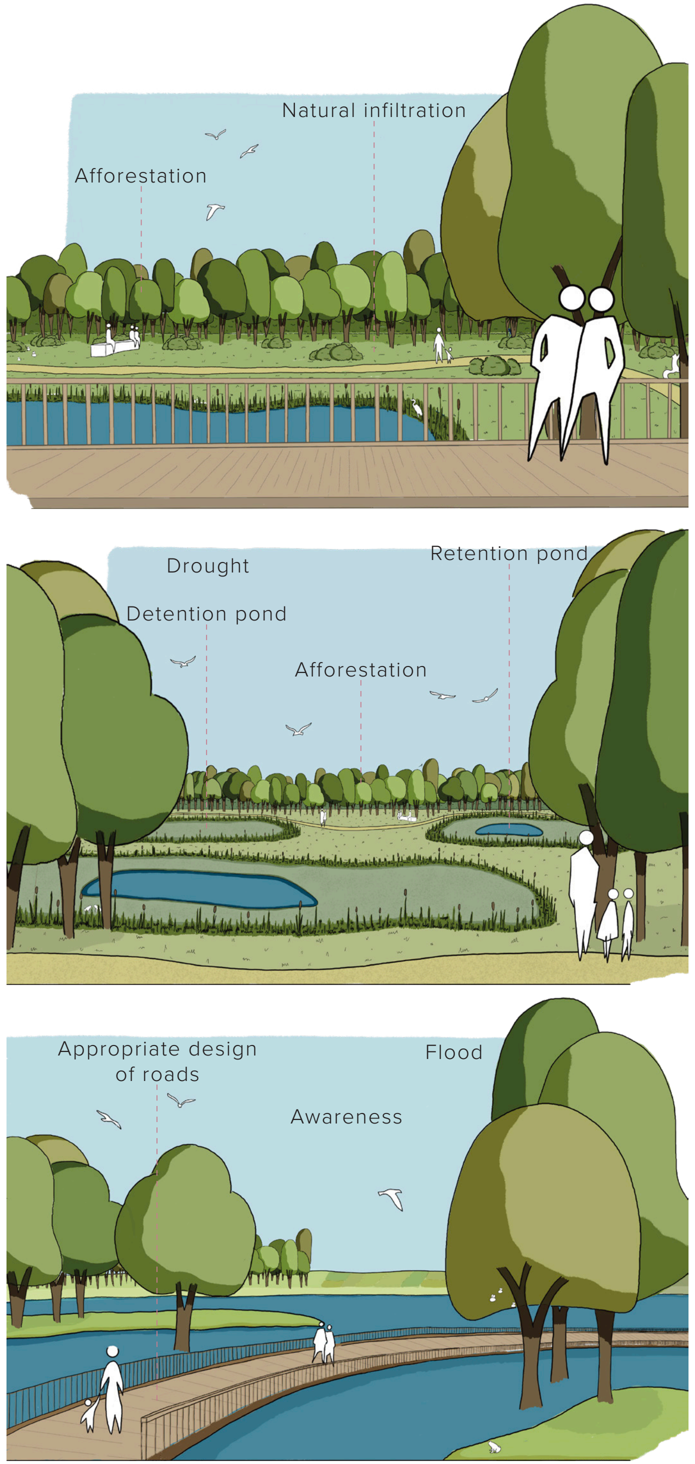
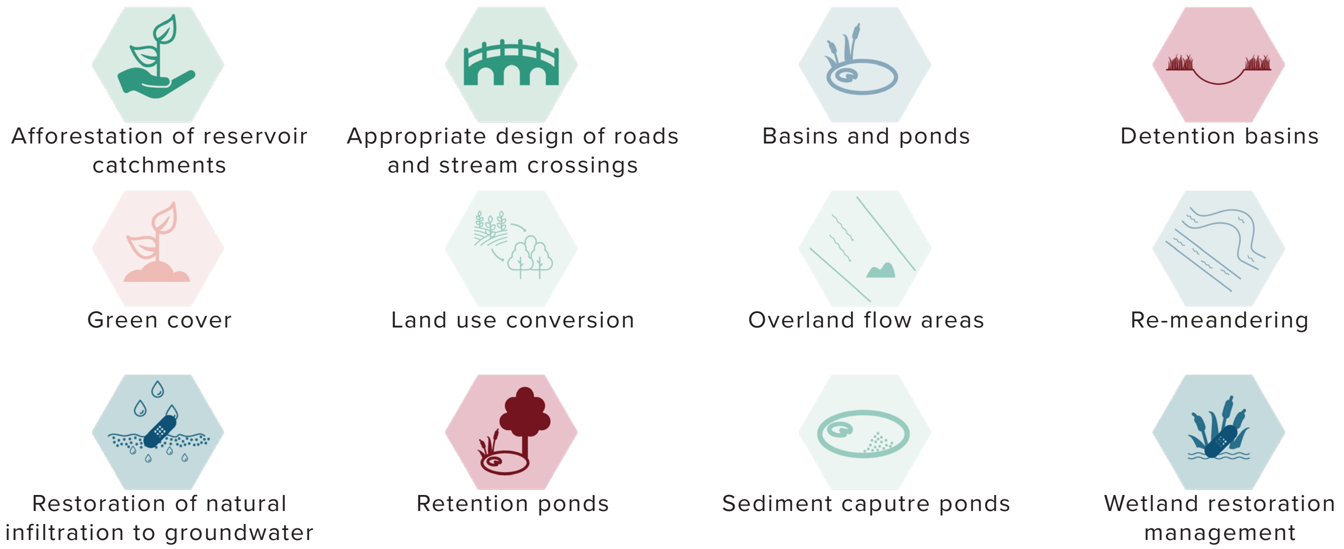


Figure 6.11 till 6.13: Views of the locations. Made by Author



For this location, the land uses wetlands and forests were selected for filtering. The following patterns were available after filtering:
Afforestation of reservoir catchments, Appropriate design of roads and stream crossings, Basins and ponds, **Detention basins**, Green cover, Land use conversion, Overland flow areas, Re-meandering, **Restoration of natural infiltration to groundwater**, **Retention ponds**, Sediment capture ponds, and **Wetland restoration and management**.

A part of this area is a bird sanctuary where people can walk through parts of the year. In this new design, the western part of the location will be closed off to people. The bird sanctuary will be extended as a **wetland**. Here bird population can flourish without human intervention. Instead, **afforestation of the reservoir catchment** will be implemented from north to south on the eastern side, which will be available for people. The forest will be combined with **retention ponds** and **detention basins**. Creating a wet landscape where people can **experience** the differences between drought, flood and the normal situation. Water has a chance to enter these locations and has free play in certain areas. This area creates a lot of **sight lines** where the different water levels can be experienced, and the **connection with the Rhine** can be made. The paths are implemented with the strategy of an **appropriate design of roads and stream crossings**. Creating paths that have little disruption to the habitat and work well with the streams. The paths should not cut off any stream paths.

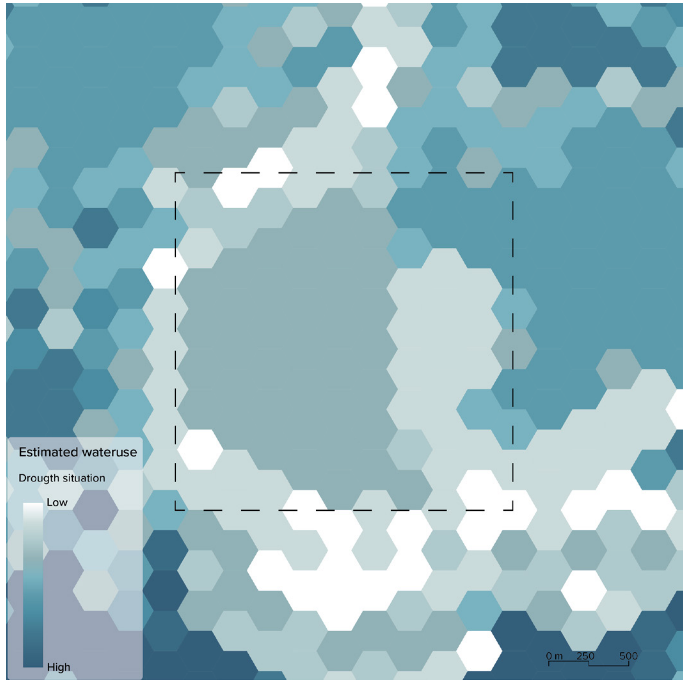


Figure 6.14: Estimated wateruse during current drought situations. Made by Author

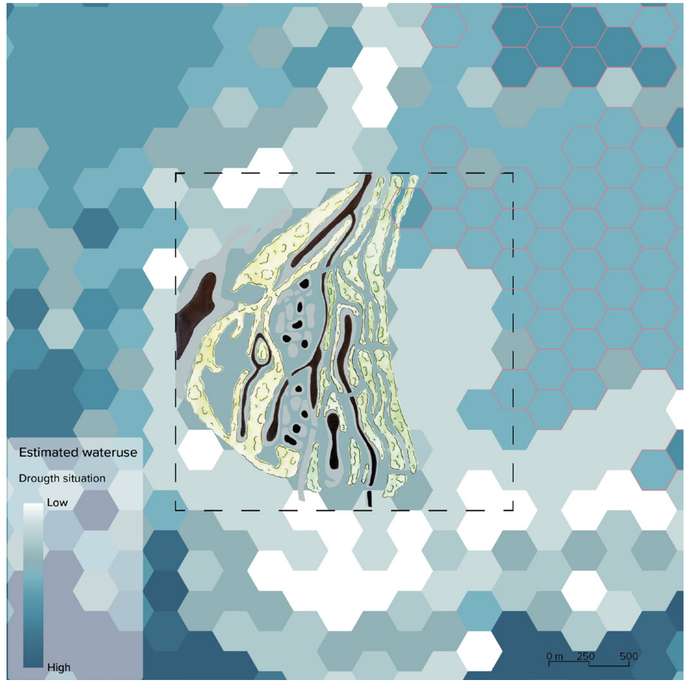


Figure 6.15: Estimated wateruse after design implementation, during drought situation. Made by Author

Figure 6.14 & 6.15 shows the current and new estimated water use. By implementing the design in this location, an impact is created in the surroundings. The need for water is reduced by creating more buffers and improving the natural infiltration to groundwater. At the same time, more buffer space is created, reducing the strain on the river. This leads to a reduction in the ask for water, as seen in the figures.

The design shows one of the green stepping stones that support the blue infrastructure. By creating an experience of flood and drought awareness will be achieved. This can lead to more support for implementing the strategies and creating a drought-mitigating river landscape.

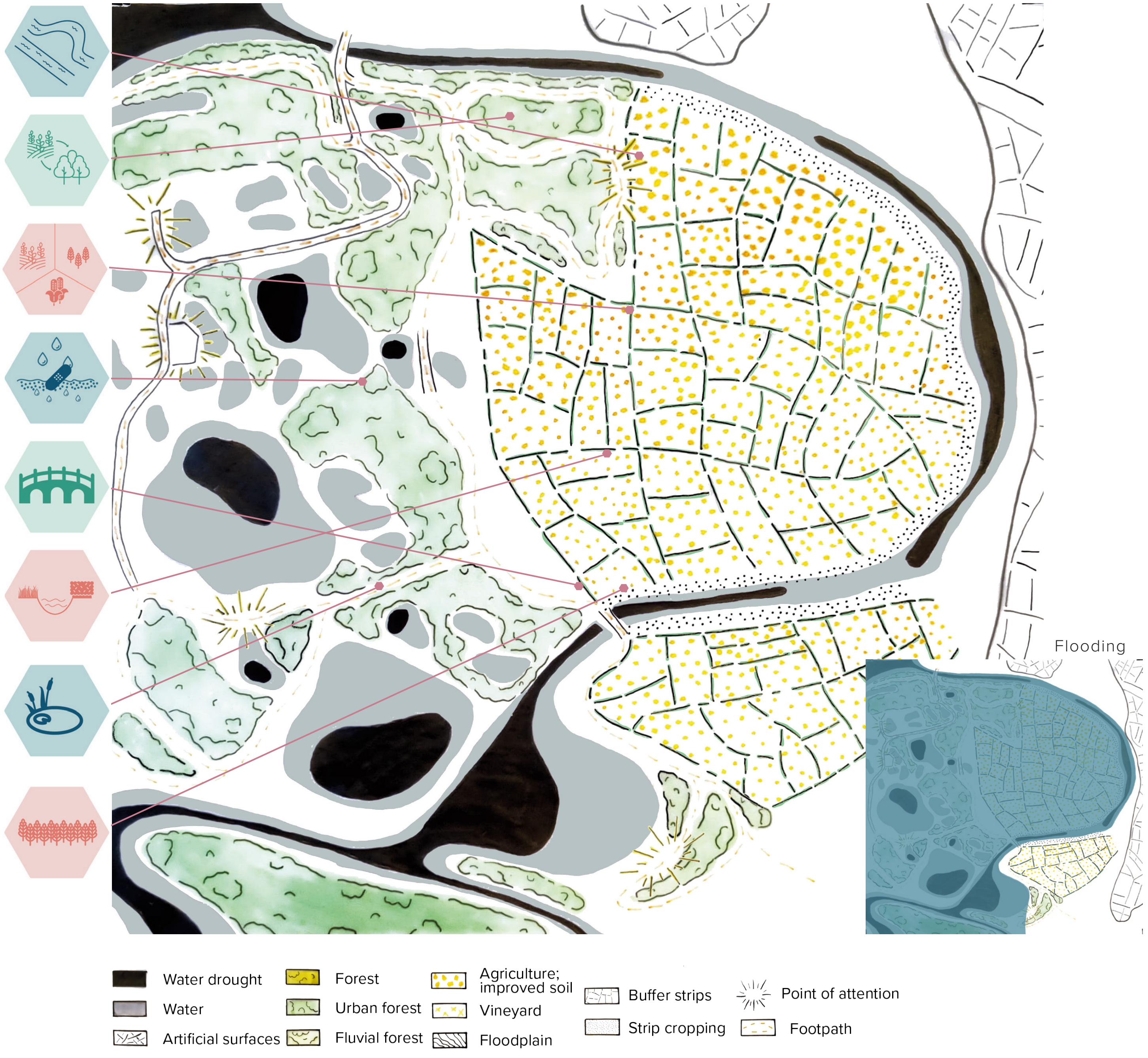
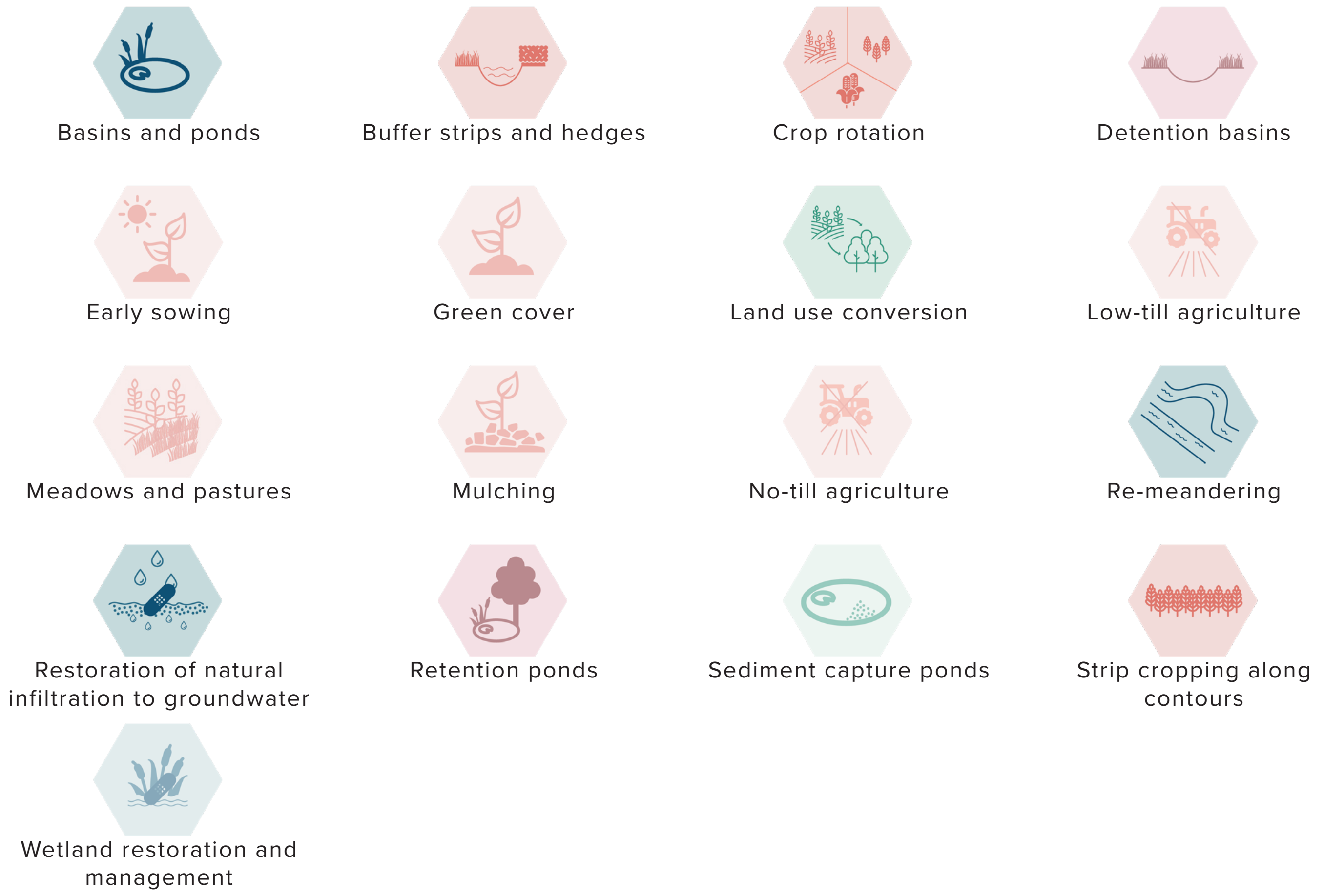


Figure 6.16: Design of Mannheim, micro scale. Made by Author



For this location, the land uses wetlands and agriculture were selected for filtering. The following patterns were available after filtering:
Basins and ponds, **Buffer strips and hedges**, **Crop rotation**, Detention basins, Early sowing, Green cover, **Land use conversion**, Low till agriculture, Meadows and pastures, Mulching, No-till agriculture, **Re-meandering**, **Restoration of natural infiltration to groundwater**, Retention ponds, Sediment capture ponds, **Strip cropping along contours**, and Wetland restoration and management.

This location has a combination of agriculture and fluvial forest. In the landscape, the old structures of a meander of the Rhine are visible. Lakes characterize the area, and artificial surfaces and the river bind it.

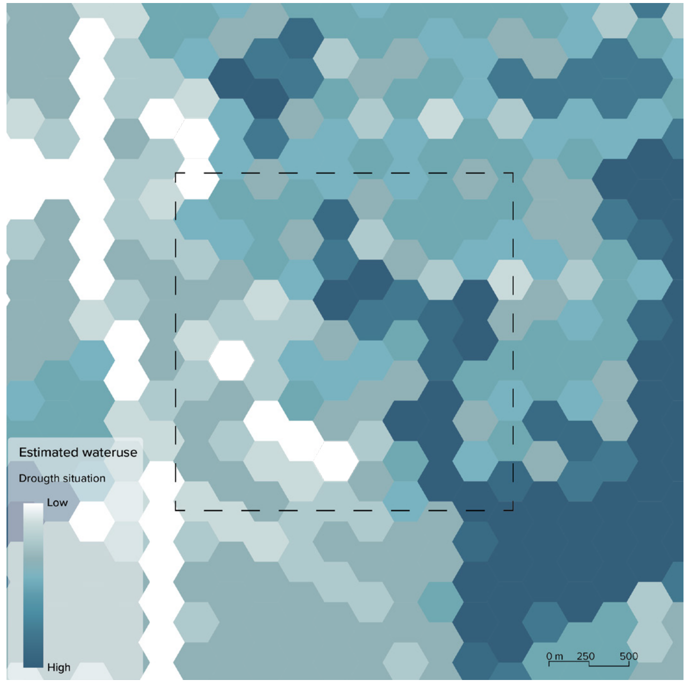


Figure 6.17: Estimated wateruse during current drought situations. Made by Author

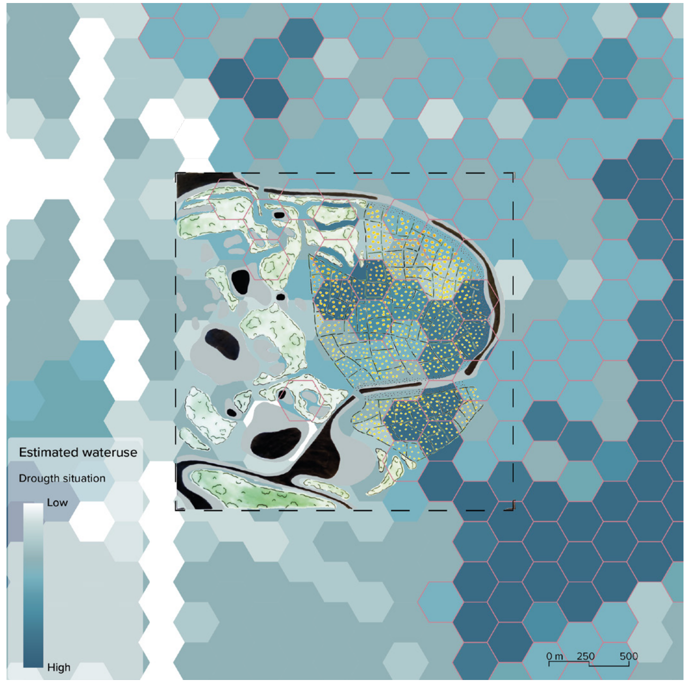


Figure 6.18: Estimated wateruse after design implementation, during drought situation. Made by Author

The traditional agricultural area has been transformed into agriculture that is more prepared for drought. By implementing **crop rotation** strategies for planting, **drought-resistant planting** can be taken into account. Using **buffer strips and hedges** to keep moisture in the area or to lead it towards the ponds during heavy rain contributes to the **stability of crop production**. **Basins and ponds** help collect this water and keep it in the area. The buffer strips, basins and ponds give water the time to infiltrate instead of creating run-off towards the river. The Rhine has been **re-meandered** in this area to create an extra buffer around the agricultural area. There is **room for the river to overflow**, and during heavy floods, the whole area can overflow, while urbanized areas stay clear of flooding. Along the meander, **strip cropping** has been applied. Strip cropping helps with **sedimentation**. In the general area, the new and diverse root structures help **restore natural infiltration to groundwater**. The recharge of groundwater will give the area an extra water resource during periods of drought.

Figure 6.17 & 6.18 shows the current and new estimated water use. By implementing the design in this location, an impact is created in the surroundings. In this design location, the impact on agriculture is especially noticeable. By having more storage, infiltration and reduced evaporation, the area has more water buffers and does not need to rely on the Rhine as much in times of drought.

The design of this area shows how an old meander can be re-meandered and how agricultural practices can become more drought resistant. The new water edge creates an accessible recreation spot for people, where fluvial forests and lakes can be explored.


Figure 6.19: Zollhafen, Mainz (Author, 2022)

6.3 MAINZ MESO DESIGN

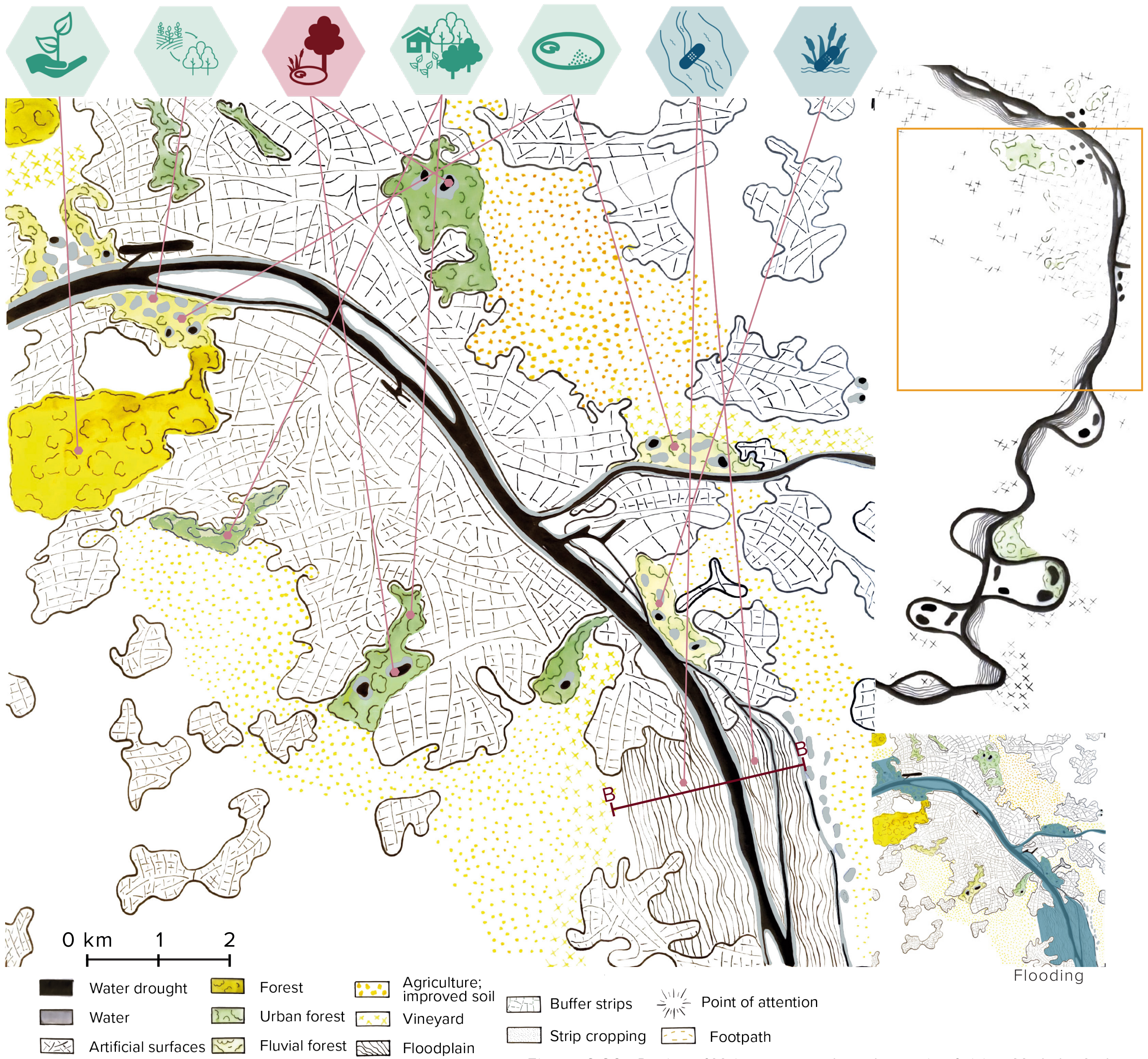
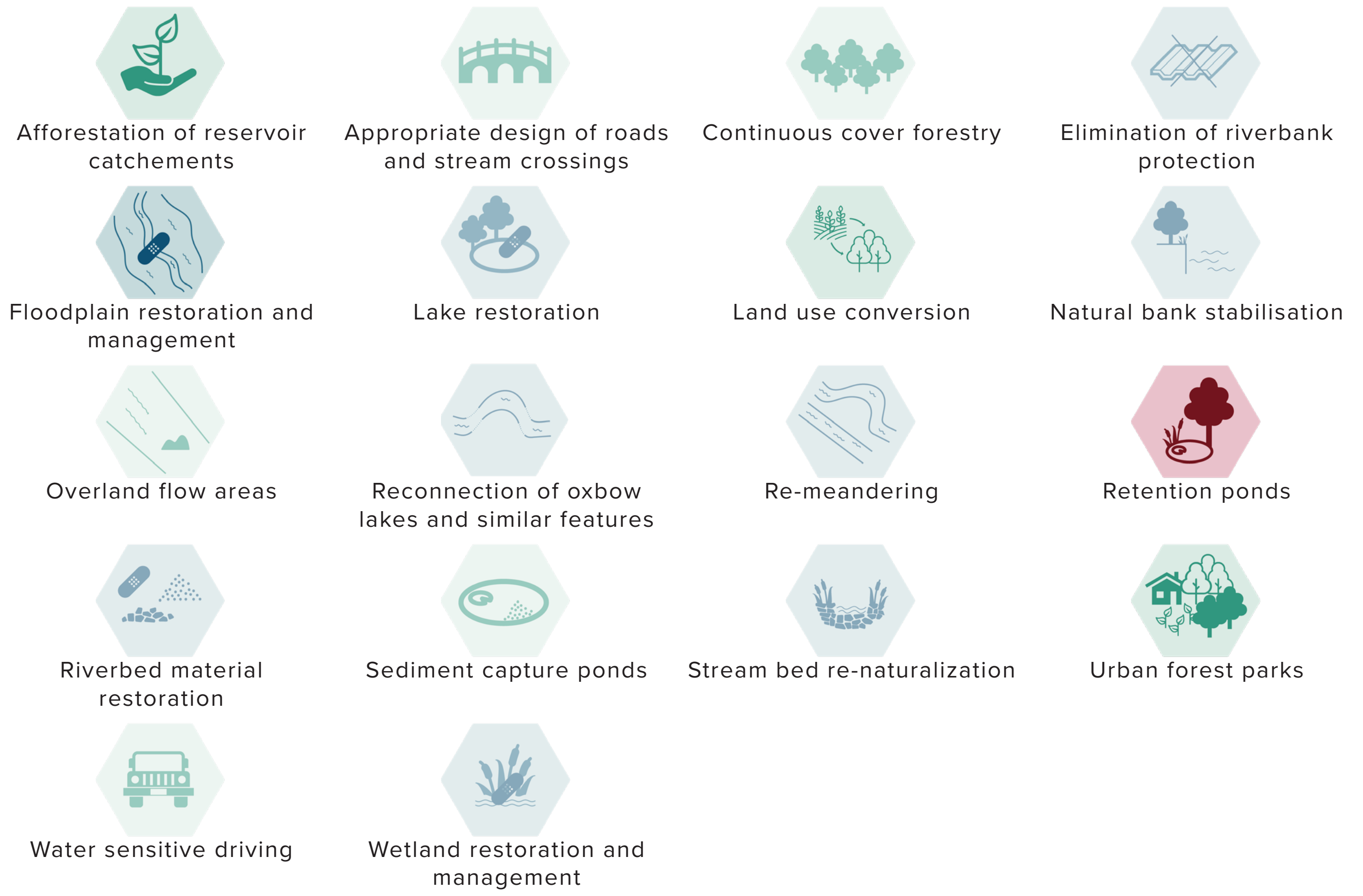


Figure 6.20: Design of Mainz, meso scale and zoom in of vision. Made by Author



Urban areas and industry characterize the location of Mainz. Here the Main flows into the Rhine River. Because of the densely built area, there is little room for water. Around the city limits, agriculture is dominant, and in Mainz, vineyards are seen around the river.

For this location, the following patterns were available after filtering. They are filtered with all different land uses still available: **Afforestation of reservoir catchments**, Appropriate design of roads and stream crossings, Continuous cover forestry, Elimination of riverbank protection, **Floodplain restoration and management**, Lake restoration, **Land use conversion**, Natural bank stabilisation, Overland flow areas, Reconnection of oxbow lakes and similar features, Re-meandering, **Retention ponds**, Riverbed material restoration, **Sediment capture ponds**, Stream bed re-naturalization, **Urban forest parks**, Water sensitive driving, **and Wetland restoration and management**.

This area has been chosen as a test area for the patterns because of its high percentage of artificial area, while there is still room to introduce new measures. In this location, there is also the inflow of a tributary, the Main. The area exists mainly out of industrial functions and agricultural functions. There is a lack of green space.

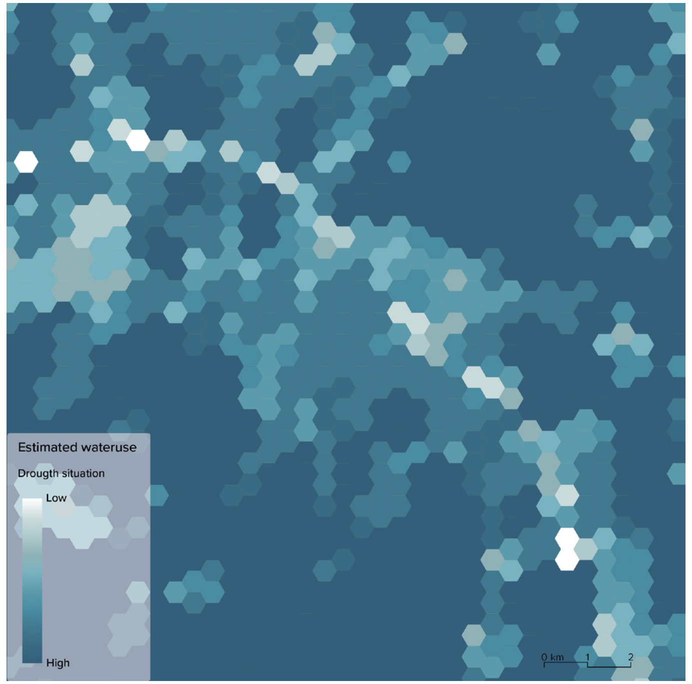


Figure 6.21: Estimated wateruse during current drought situations. Made by Author

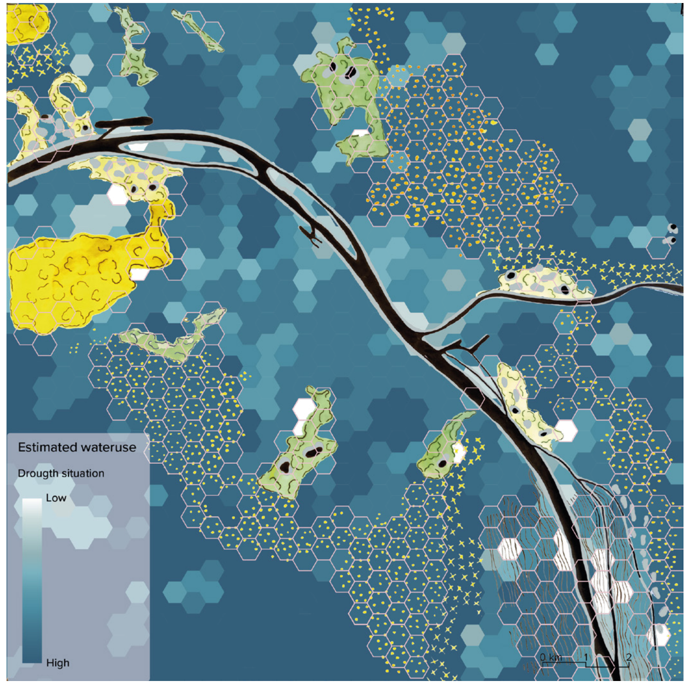


Figure 6.22: Estimated wateruse after design implementation, during drought situation. Made by Author

By introducing **urban forest parks**, there is room to let water infiltrate the groundwater. The roots of trees improve the soil quality and will also prevent erosion. With urban forest parks, space for humans to enjoy green spaces and gain the benefits these spaces have for their well-being.

As well as urban forest parks, **afforestation** is gained in this area. Creating two types of forest, where one is characterized by its **fluvial forests**. Having multiple types of forests creates **habitat diversity** around Mainz.

Spots with **retention ponds** are combined with forests to lessen the impact of evapotranspiration. The retention ponds can be used as support for agriculture in times of drought and help with **catching run-off** during excessive precipitation. Retention ponds near large industrial spots have also been implemented. These ponds can help with the water resources the industry need.

Near the waterfront, **sediment capture ponds** are placed. These sediment capture ponds can help with the **water quality** of the Rhine by preventing contaminated agricultural run-off from entering the river's streamflow before it has time to be filtered by plants.

Along the southern part of the area, **floodplains** have been **restored**. In the landscape, traces of old floodplains were noticeable, and these have been

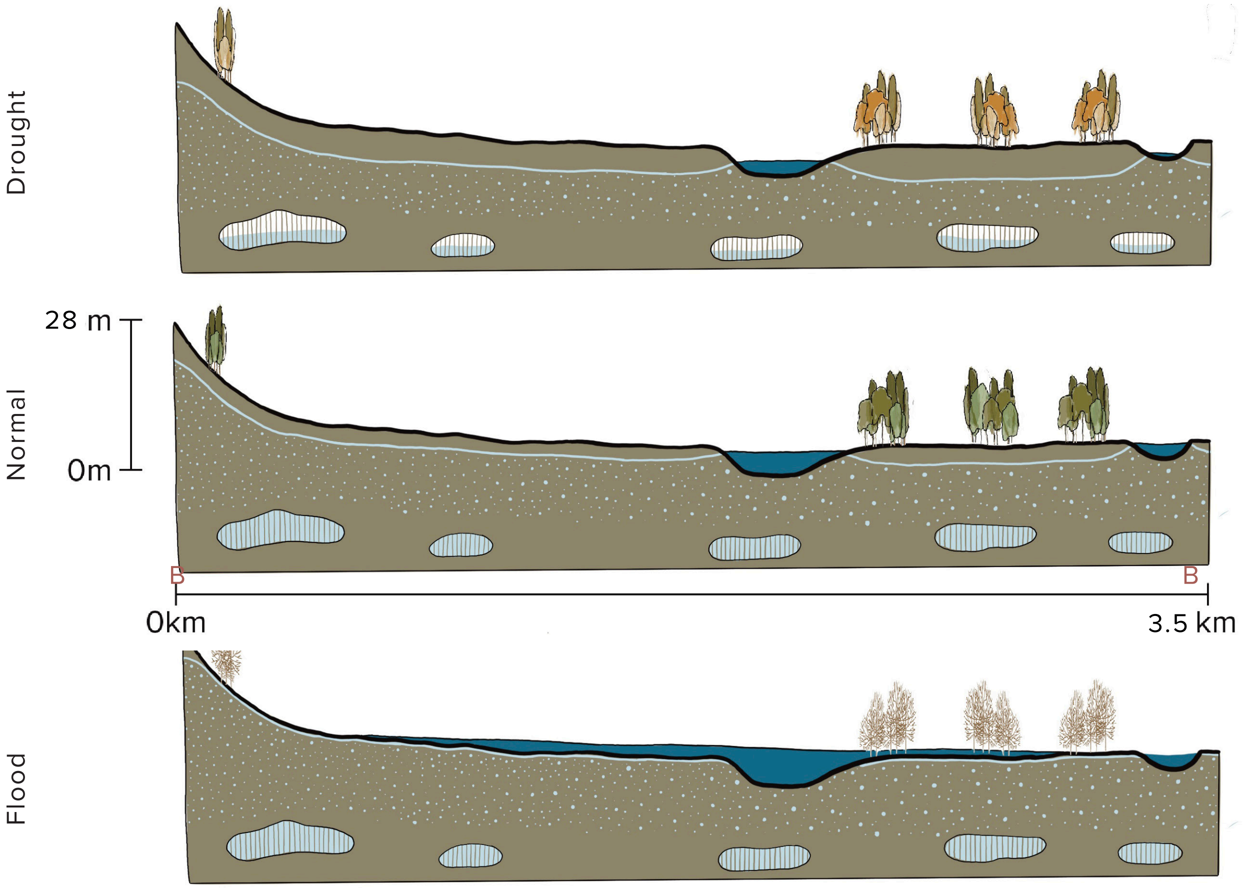


Figure 6.23: Sections of the Rhine and surrounding, Mainz. Made by Author

again implemented to improve the **storage capacity** of the area during times of flood.

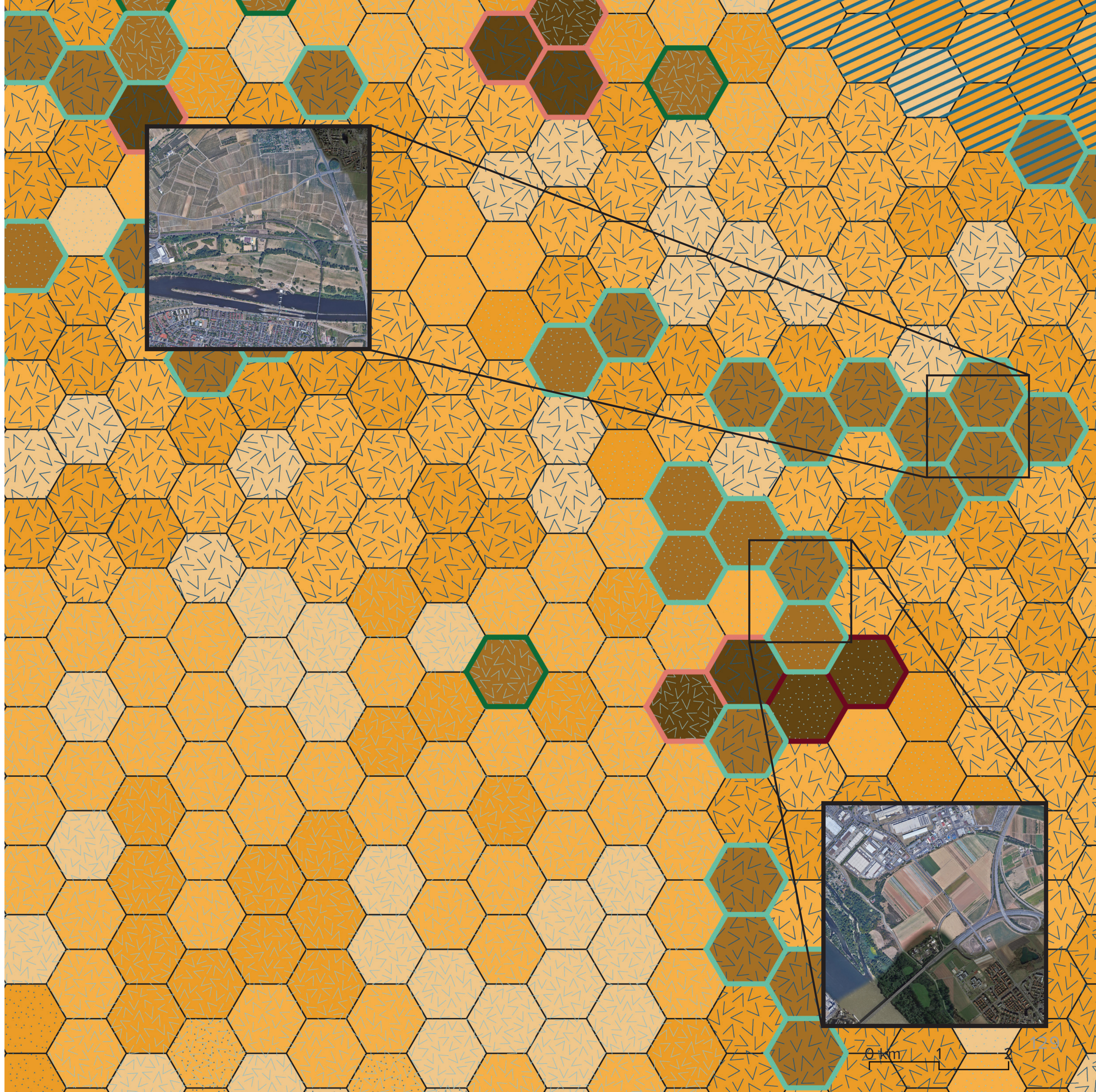
On the vision map, it is noticeable that Mainz is in a turn of the river Rhine. Mainz is also the point where the old meanders of the river stop from showing up in the landscape. Before Mainz, a lot of room for flooding and infiltration is implemented, as this is hardly possible around Mainz itself. During extreme flooding, Mainz has this buffer to cope with the amount of water and can deal with the water that falls locally by using the retention ponds and other parks. Around Mainz, green hotspots are created to continue as a stepping stone of green infrastructure to support the blue infrastructure in place.

The difference between groundwater and surface water levels can be seen in the section (figure 6.22). The height along the left bank quickly rises, creating a lot of run-off towards the river. The area has a lot of agriculture, and a floodplain makes this land flood during wet periods. The artificial areas stay dry. Aquifers can be replenished and support the area during periods of drought.

6.4 MAINZ MICRO DESIGN

To determine the design location for the small-scale design for Mainz, different analyses have been combined to create an insight into suitable design locations. For these locations, an area that can show many different pattern implementations would be most suitable. This led to the creation of a grid that counted the number of different functions. The spots with the most diverse functions are then combined with the different types of aquifers. By combining these two different analyses, selected areas that are most diverse from these two locations were picked to design.

Figure 6.24: Location determination for micro scale Mainz. Made by Author -->



0 m 250 m 500 m

Figure 6.25: Design of Mainz, micro scale. Made by Author

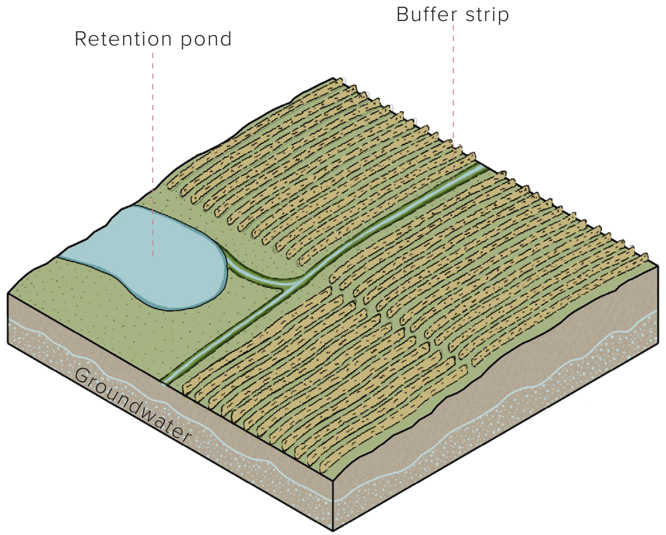


Figure 6.26: Axonometric view of the design location. Made by Author

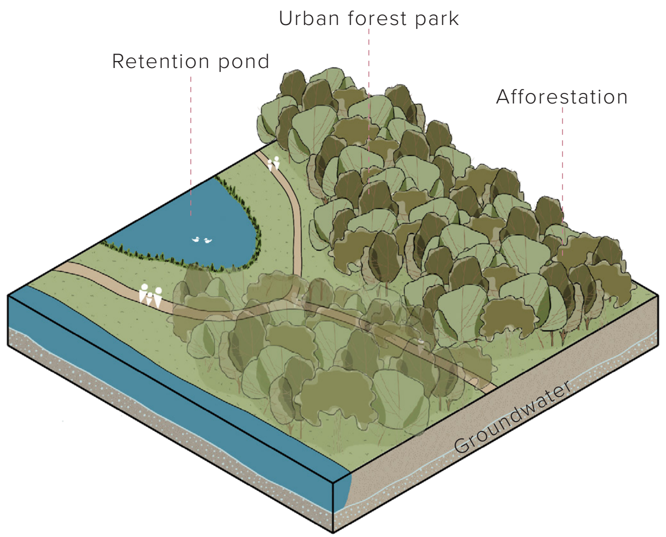


Figure 6.27: Axonometric view of the design location. Made by Author

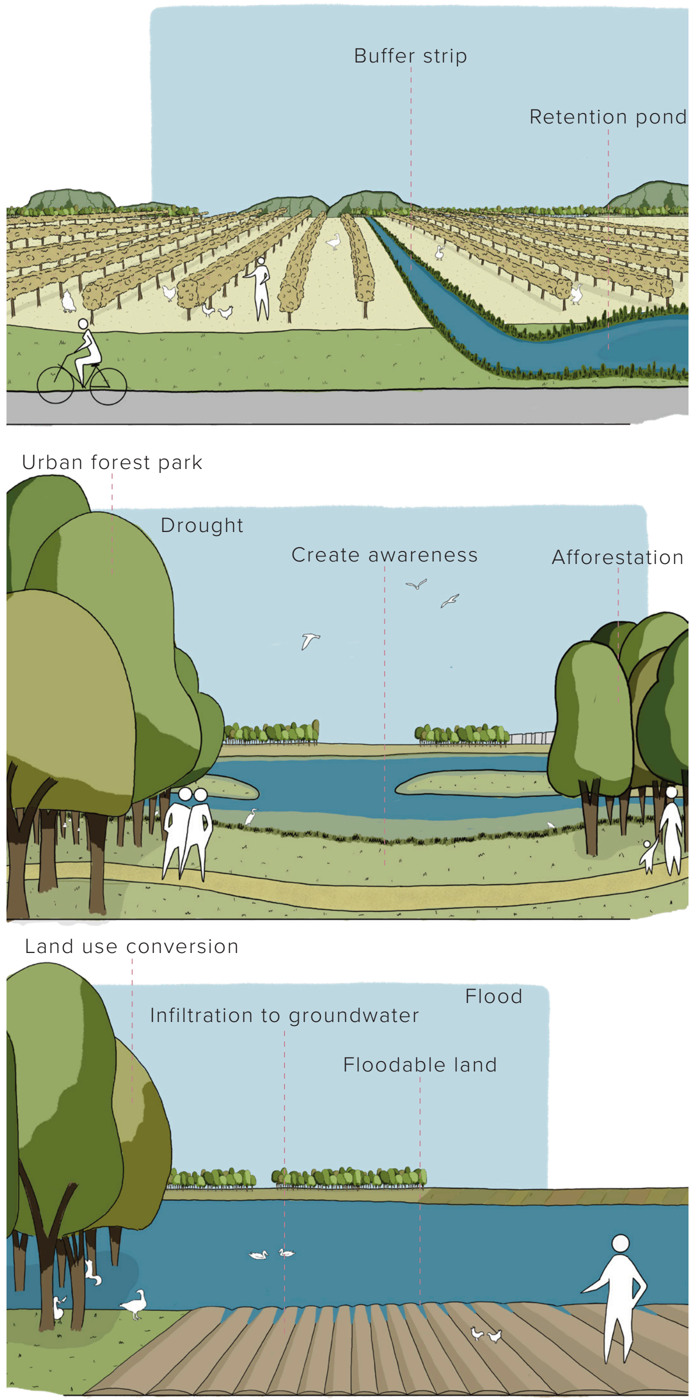
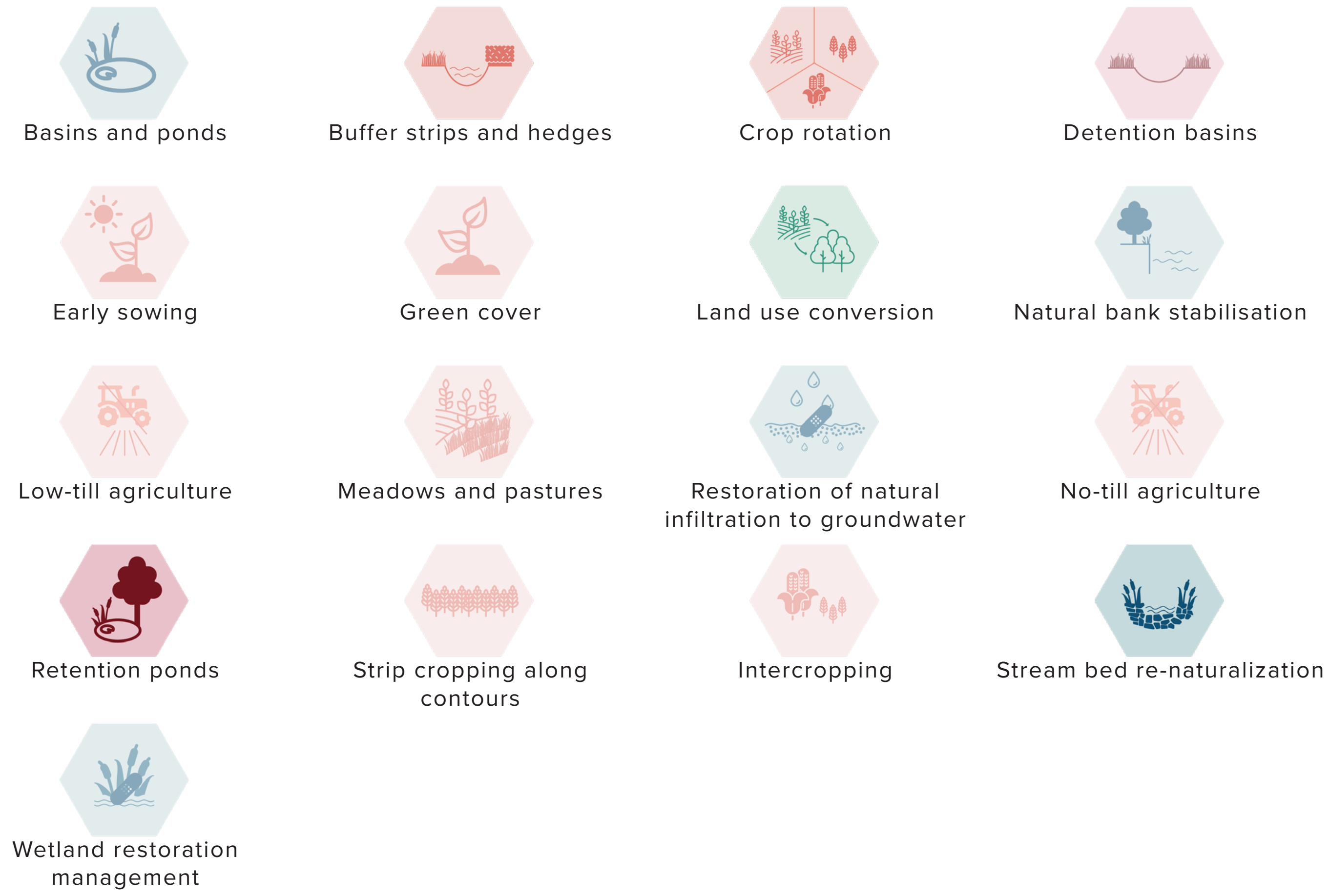


Figure 6.28 till 6.30: Views of the locations. Made by Author



For this location, the land use agriculture was selected for filtering. The following patterns were available after filtering:
Basins and ponds, **Buffer strips and hedges**, Controlled traffic farming, **Crop rotation**, Detention basins, Early sowing, Green cover, Intercropping, **Land use conversion**, Low till agriculture, meadows and pastures, Mulching, **Natural bank stabilisation, No-till agriculture**, Restoration of natural infiltration to groundwater, **Retention ponds**, Stream bed re-naturalization, Strip cropping along contours, and Wetland restoration and management.

This design focuses primarily on creating buffers for agriculture and vineyards. The area has an extensive vineyard on the northern side. There is agricultural land use along the river bank. Because of the height difference in the area, run-off towards the Rhine occurs quickly.

Water collected with **buffer strips and hedges** can be stored in **retention ponds** and slowly infiltrate into the groundwater. By implementing a structure of buffer strips between the vineyards, water can be collected and held onto in the same spot. This way, precipitation stays longer available for this area and does not run off towards the river.

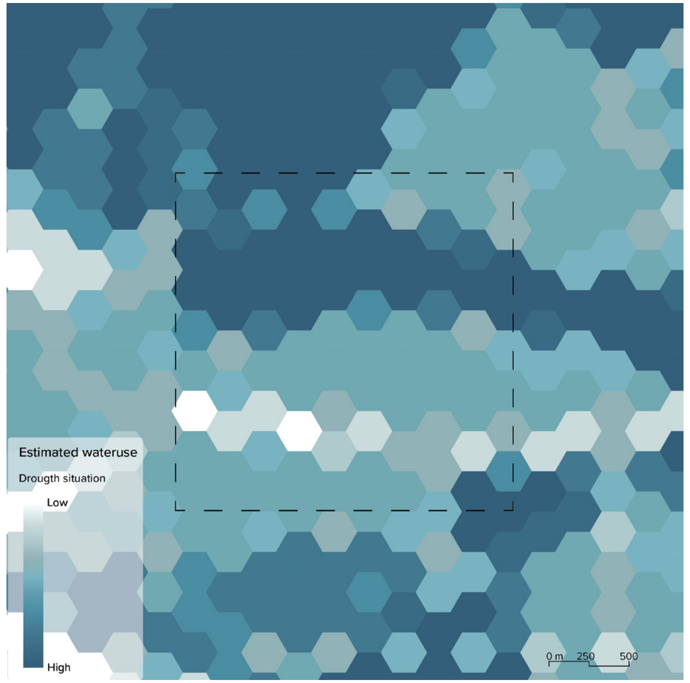


Figure 6.31: Estimated wateruse during current drought situations. Made by Author

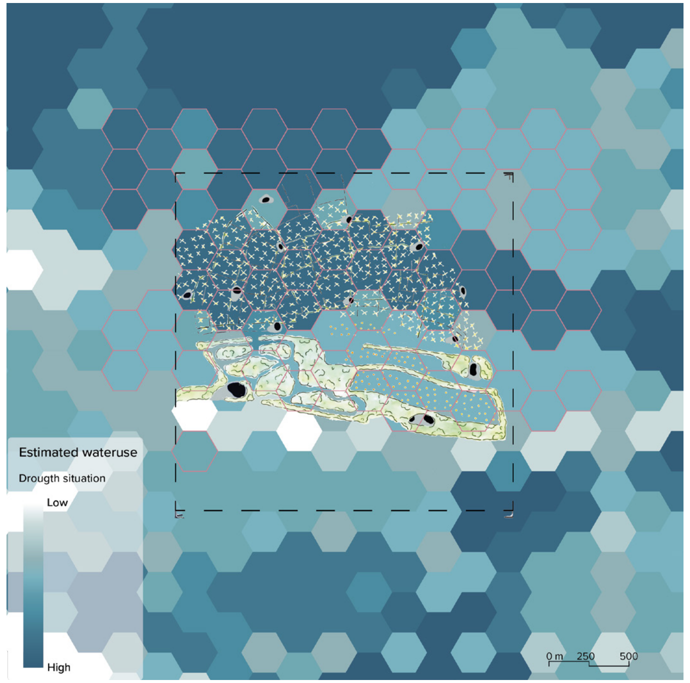


Figure 6.32: Estimated wateruse after design implementation, during drought situation. Made by Author

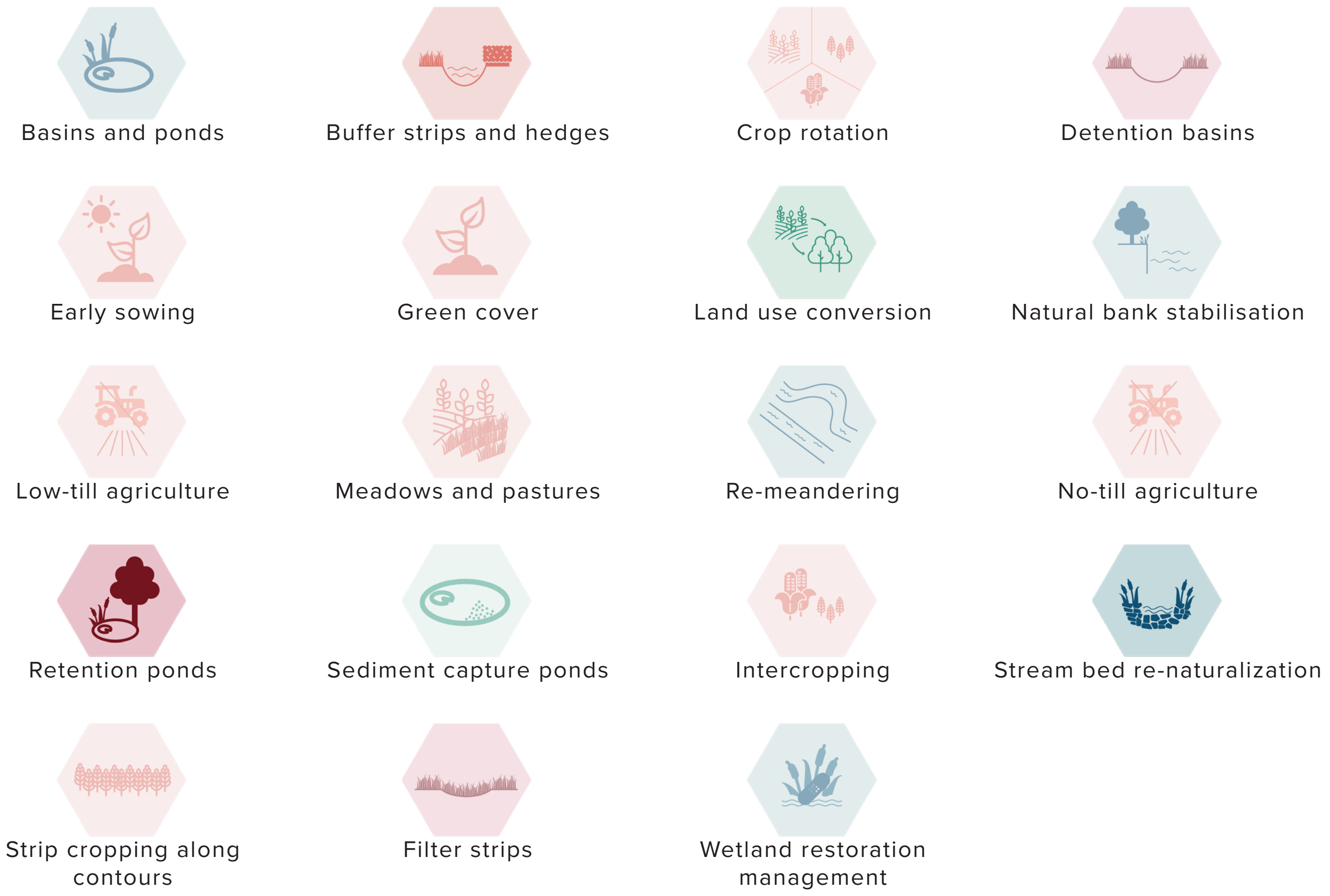
By implementing **crop rotation** with **no-till** agriculture, the soil quality of agriculture will be improved. This will help with the natural infiltration. During extreme flooding, the agricultural space can be used to store water from the river. The southwestern part of the area has been **converted** into green space. The water structures that run through this space have been implemented with **natural bank stabilisation** to allow animals to move from bank to bank. This helps **improve the biodiversity** of the area.

Figure 6.31 & 6.32 shows the current and new estimated water use. Implementing the design in this location creates an impact on the surroundings.

By holding on to water in the vineyards, the pressure on the Rhine will be decreased for supplying water. Along the agriculture at the river bank, soil infiltration will be improved and evaporation reduced with a new green structure.

The design area shows how vineyards along the Rhine can be more drought resistant by creating buffer strips to hold onto water. This type of measure can be applied to any sloped agricultural area. The river can extend to the agricultural area in times of need, creating a buffer for Mainz when flooding is inevitable.

Figure 6.33: Design of Mainz, micro scale. Made by Author



For this location, the land use agriculture & wetland was selected for filtering. The following patterns were available after filtering:
Basins and ponds, **Buffer strips and hedges**, **Crop rotation**, Detention basins, Early sowing, Green cover, Land use conversion, **Natural bank stabilisation**, Low till agriculture, Meadows and pastures, Re-meandering, **No-till agriculture**, **Retention ponds**, **Sediment capture ponds**, Intercropping, Stream bed re-naturalization, Strip cropping along contours, Filter strips, and Wetland restoration and management.

This design focuses mostly on the creating buffers for agriculture and industry. The area is bounded by industrial companies. The agriculture has been adjusted to create more drought resistant crops.

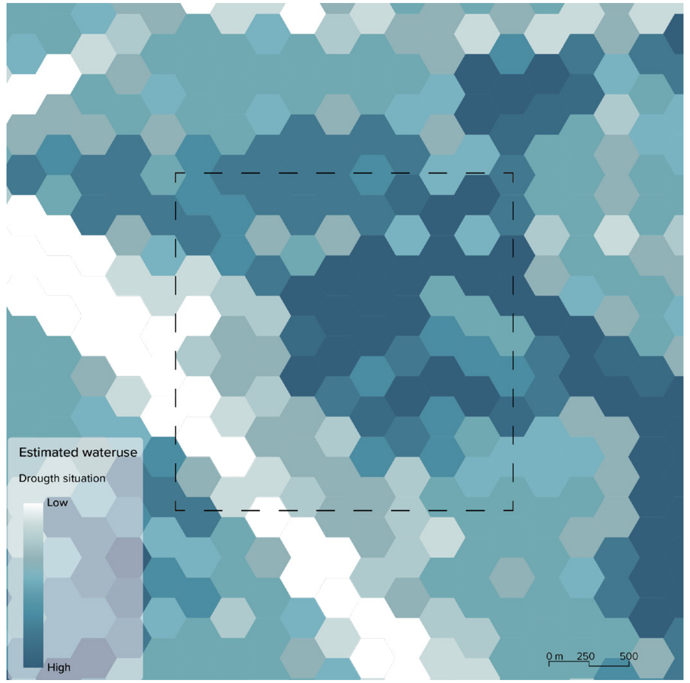


Figure 6.34: Estimated wateruse during current drought situations. Made by Author

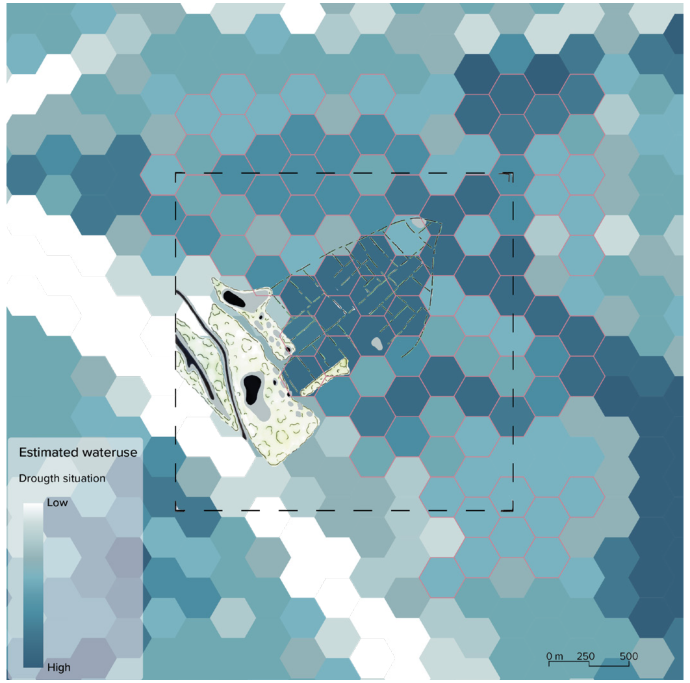


Figure 6.35: Estimated wateruse after design implementation, during drought situation. Made by Author

Water collected with **buffer strips and hedges** is stored in **retention ponds** in the area and around the industrial sites. With this structure, precipitation is kept in the area and has time to infiltrate. The retention ponds also provide a **buffer** during times of drought. The agriculture will be transformed into **crop rotation agriculture** with **no-till agriculture**, creating **better soil structures** and with will help **recharge aquife**rs. **Sediment capture ponds** are implemented at the lowest point of the run-off paths of the agriculture. Here excess run-off will be captured and filtered, **improving water quality** of the area and the Rhine.

Figure 6.34 & 6.35 shows the current and new estimated water use. Implementing the design in this location creates an impact on the surroundings. The agriculture will have a lower demand for water as there is more storage available. The industrial practises in the area will also have less of a demand for water and can be combined with agricultural water needs.

The design area shows how agriculture and industries can work together to create a better system to be prepared for drought events. With limited room available the storages options can be combined and synergies can be created.


Figure 6.36: Pfalzgrafenstein Castle, Kaub (Author, 2022)

CONCLUSION & REFLECTION

7.

Figure 7.1: Rhine landscape with a castle, town and church, boats and figures (Franz Hochecker, 1782)

7.1 CONCLUSION

Analyses

To understand the environmental impact of drought on functions of the Rhine.

1. How does streamflow drought impact the Rhine and the surrounding landscapes?
Streamflow drought has a severe impact on the Rhine and its surroundings. In general, during drought, the streamflow shows a significant depletion in discharge, affecting the many functions of the Rhine. At the same time the demand for water rises, but the availability does not. Drought impacts the ecological system and habitats. The lack of water over several years can lead to permanent damage to ecosystems from which they cannot recover.

To understand the social impact of drought on functions of the Rhine.

2. How are the functions of and on the Rhine affected by drought?
The impact is noticeable in the agricultural sector, where crops are affected due to a water shortage. The industry is severely affected: due to low water levels, shipping gets obstructed, and supplies cannot be delivered. The temperature of the river water will rise, making it unsuitable for cooling. This can have consequences, for example, for the energy supply. All this negatively impacts the living conditions, economy and recreational values around the Rhine.

To find solutions to combat the impact of drought on functions of the Rhine

Vision

3. How can the green-blue infrastructure approach be used to form a synergy between urban and rural river landscapes?
By implementing the green-blue infrastructure approach, a network of ecosystems is created with a cross-border approach. The new green-blue measures add to habitat diversity or allow new habitats to develop. By using rural areas to implement the large implementations of this strategy, the effect of drought on living-, economic-, and recreational conditions can be improved and will positively affect the urban areas. To create this positive effect, using urban as well as rural landscapes is necessary. The lack of space can be addressed by forming a synergy between the two. The interaction between humans and nature that this synergy will stimulate, has many positive benefits for humans. By implementing the green-blue infrastructure approach, many opportunities for access to green spaces occur, increasing positive interactions and overall well-being.

Strategy

4. How can nature-based solutions be used for drought-mitigating strategies along the Rhine?
Nature-based solutions are actions that work with nature and its ecosystem. They are individually implemented, but by using them as support for the green-blue infrastructure approach, they strengthen the strategy, creating a more multiscalar solid approach to mitigate drought problems.

For Every Drop Counts, the nature-based solutions are incorporated in a pattern catalogue that describes the different actions that can be taken to mitigate drought around a riverscape. The pattern catalogue is based on the European Natural Water Retention Measures that promote the use of nature-based green infrastructure solutions. These measures are transformed into patterns, showing the effects of physical impacts and environmental changes.

To explain the patterns, pattern fields are created in the Pattern Catalogue. These pattern fields represent challenges commonly encountered in the built environment. For Every Drop Counts, the pattern fields can be used to help identify suitable implementations. After creating the pattern fields, seven different patterns were identified that are applicable to various situations. These seven patterns are the starting point for the design.

A filtering system has been implemented to create an insight into the applicability of each pattern. This system filters out the patterns that apply to specific design locations to create a robust research-based design. By following the steps described in the thesis, a set of patterns will be found that narrows down to the suitable patterns for the specific design location and situation.

Design

5. How can the desired drought-mitigating strategies be implemented along the Rhine?
This research culminates in a pattern catalogue with drought-mitigating measures applicable along the Rhine. When a design location has been selected, these patterns can be selected based on a set of predetermined filters. The filters give the most suitable design solutions to mitigate drought in that area. This strategy creates a robust, research-based design.

Main research question

How can the river Rhine stay a functional riverscape by creating a synergy between urban and rural areas while using the green-blue infrastructure approach to mitigate drought-related problems?

To create a functional riverscape during streamflow drought, the Rhine will have to use all available water throughout the seasons. To mitigate the drought problems, a synergy between the urban and rural areas has to be created. The lack of space in the urban areas leads to a need to combine strategies with the rural areas where more space is available. The different land uses can be connected to create a better drought-mitigating strategy. For example: At locations in rural areas subjected to flooding, space can be created for infiltration and recharge of groundwater and aquifers. For this, it is essential to know what each area around the Rhine has to offer and what type of drought-mitigating measures are most suitable to implement.

The green-blue infrastructure approach creates a network of ecosystems. By implementing nature-based solutions in this network, it becomes a strong cross-scale network. The focus of the network is on drought mitigation. The implemented nature-based solutions are based on their drought-mitigating capabilities. The green-blue infrastructure helps the network to become resilient.

The nature-based solutions embedded in this infrastructure are translated into a drought-mitigating pattern catalogue. This multiscalar pattern catalogue can be filtered for different types of landscapes, land uses, and more requirements. This approach leads to a selection of measures that apply to different landscapes. By implementing the green-blue infrastructure approach in rural and urban areas, a functional riverscape during streamflow drought can be created.

7.2 REFLECTION

This project aims to create a resilient river landscape during streamflow drought. Building up a drought-mitigating pattern catalogue that focuses on creating a green-blue infrastructure by implementing nature-based solutions that will reduce the impact of drought.

Relevance

This thesis aims to create design solutions to improve living-, economic-, and recreational conditions during periods of drought. By implementing drought mitigation measures, there is less impact caused by drought on society. Low water levels during streamflow drought can significantly impact functions on and around the Rhine. At the same time, this affects habitats around the Rhine and can cause a decline in biodiversity. By creating a design strategy that will create a more drought-resistant riverscape, the impact on society will be reduced, and living conditions will be improved, as well as awareness of drought. The awareness can result in a more hands-on approach and more willingness to mitigate drought and act on the climate crisis. This results in options for implementing drought mitigation solutions and creates an easier way to choose between many possibilities.

The scientific relevance of this thesis is mainly about the knowledge gap around climate adaptation research. When it comes to water-related events, flood has been very well researched, but drought, on the other hand, is lacking in the amount of research. In the field of urbanism, this gap is very noticeable. Regarding design research, many different strategies have been tested for flood. Still, drought comes as an extra in these scenarios and is hardly ever the main reason for a new climate adaptive design, especially in Europe. This thesis looks at the river Rhine from a flood perspective and creates a strategy that will use flood events to mitigate drought.

By creating a data set that acts on different geomorphological typologies, and various land uses and looks at what type of river structure it is implemented on, this data set can be applied to many more river structures. Furthermore, this research creates a pattern catalogue with data set for filtering these patterns. This data set can be transferred to other rivers, extended, and used to develop even more extensive knowledge for drought-mitigating solutions.

During my work on this thesis, I gained a lot of experience. My personal scientific relevance is partly the fact that I had no experience working on this scale. Research that overlaps multiple countries and follows a river as the basis for the study was entirely new for me. As my usual way of analysing would not work for this area, I quickly had to adapt to interpreting the data differently. I managed a data-driven approach to the analysis with the help of my mentors. I created a grid structure to process the data into readable analysis that could be compared, layer to layer.

This project also taught me a lot about the availability of data outside the Netherlands and how data from different countries combined can lead to many gaps in this data. Data availability is not the same in every country along the Rhine. Many of the data ended up being more generic data sets from the European Union, but those did not always include Switzerland and still left a gap in the data.

My focus had never been on drought mitigation. But apart from that, during my study, I was involved in projects that involved climate adaptation strategies. These projects were, like most, based on flooding events or heat waves. During this project, I gained a lot of knowledge about drought and how this affects the habitats in Europe. This knowledge is an excellent addition to the knowledge I have gained over the years and will hopefully lead to more well-rounded projects in the future.

Approach

This thesis has its foundation in drought mitigating measures with a nature-based solution approach. The aim is to create a vision for the Rhine that includes a green-blue infrastructure approach. This approach is strengthened by implementing the nature-based solutions on a small-scale design to show the implementation of the green-blue infrastructure on a more detailed scale. With this approach, the drought mitigating measures are limited from the beginning. This limitation helped keep focus and not overextend the solutions, as there are many options. Therefore choosing a specific direction helped with keeping on track.

Because of the chosen location, this thesis needed a different way of approaching the analyses. This approach is the creation of a hexagonal grid over the data sets. By transforming the data into a hexagonal structure, it was easier to compare the different data sets and create conclusions. This structure helped a lot with the readability, but the main issue with this approach is partial data loss. Because of the hexagonal structure's scale size, only the most considerable areas were calculated. But this might be necessary for an area as big as the Rhine catchment. Without the reduction of detail, the analyses would be almost impossible to make, and conclusions would have to be too detailed to be of any interest.

The hexagonal shape chosen to analyse the data lies in the efficient use of space in the shape. Because of their efficient use of space and structural integrity, hexagons are often found in nature, for example, in honeycombs or basalt columns. The hexagon is used in data processing because of its unique properties, and it can evenly fill an area without gaps or overlaps. Hexagons are also an appealing way to represent data, as Wilke (2019) describes in his book Fundamentals of Data Visualization. Hexagonal binning is an excellent tool to analyse and visualise large datasets properly. It provides a balance between oversimplification and too much detail. This then helps with the interpretation of large datasets.

The hexagonal analyses helped with the determination of the design locations. With this approach, it was easier to locate the locations that would have the different demands needed to fulfil the needs of the design locations. In this way, different design locations were easy to point out.

The pattern catalogue created during this thesis is based on the Natural Water Retention Measures from the European Commission and Office International de l'Eau (2014a). This catalogue contains an extensive overview of nature-based solutions that apply to streamflows and surrounding areas. In this thesis, the catalogue is transformed into a pattern catalogue that can be filtered to find the best measures applicable to the needs of the design location. While finding the best filter criteria, many problems were accounted for. It was hard to find the proper filter settings that did not take too many pattern options. At the same time, the list should not remain too long, as this makes taking design decisions still hard. Using this pattern catalogue as a basis for designing the project could be implemented in a different location by implementing the same data set.

Using the Natural Water Retention Measures from the European Commission and Office International de l'Eau (2014a), the pattern catalogue has a multi-scale approach. Different types of patterns will show up for different design scales when filtering for the applicable patterns for the design. This filtering makes a more detailed design strategy possible, as not every scale will show the same measures, but these measures can enhance one another on different scales. During the design phase of this project, the patterns were tested on multiple scales to see the differences in design and the way these designs strengthen each other through the scales. Large scale design shows the green-blue infrastructure approach more, while the small scale shows the implementation of specific patterns with a nature-based solution approach. The medium scale has an overlap of these two implementations. They are showing a part of the green-blue infrastructure and more comprehensive nature-based solutions.

The pattern catalogue, as is, is not definitive. Many more options can be added to the data set and included in the filter actions. This way, the knowledge about drought mitigating measures can be extended, creating an extensive and fully applicable pattern catalogue. As there were limitations to time, it was chosen to keep the pattern catalogue to the basis. There are many more patterns to add. Added patterns could be for example, a pattern that would describe the possibility of flooding agricultural land when needed, where water collection can take place to store water for times of drought, would be one. Or a pattern that describes the reuse of water for industrial purposes. These patterns could be added in later research.

During this thesis, an iterative approach was an important component. The relation between the patterns and the designs is sharpened with each step. By trying the patterns on the design, you realise that something might be missing or you have too many options. This process leads to ~~trying~~ new filter settings and gaining new types of patterns to try on the design. After a few tests, an appropriate filter setting was found and kept. But this iterative process could continue for a few more rounds to find more flaws. Unfortunately, this is not an option in this thesis due to time constraints. The current filter pattern works fine for this design, but when tested on different locations, other problems might pop up that could help tweak the filter settings a bit more.

The end goal of this project is the simplification of designing for drought and being able to tell the impact of the design implementation on drought mitigation. Getting to this process of trying to design with an incomplete set of filters was hard. It took a few tries to figure out how to design like this and let go of the need for perfection.

Every drop counts, and urbanism

This project focuses on implementing large-scale drought-mitigating measures that follow a green infrastructure approach to keep the Rhine and surroundings functional during drought. The chosen master's track, urbanism, aims to create a broad perspective on research and design. For this project, the context lies within the interference of functions in and around the Rhine brought on by drought. With this subject, the project aims to look at drought from an overall perspective and create a broad perspective on research and design. There is common ground with topics like environmental problems, sustainability, climate adaptation and social-ecological emergencies.

This project's design focuses on the synergy between rural and urban landscapes and headwater and downstream areas. The design is multiscalar from large-scale vision to more detailed design implementations while working with pattern language. This multiscalar design approach gives an overview of how one area can have different details and experiences when going through the scales.

Every Drop Counts is an urbanism project because of its basis of combining research and design to create a pattern catalogue that fills a gap in designing to mitigate drought problems.

Ethical considerations

The thesis Every drop counts has some ethical considerations to name. The first one is the language, cultural and governmental barriers that exist in the project area, the catchment of the Rhine. The expectations for projects are different, and each country has different needs, which can lead to disagreements between involved parties. The history and differences in governmental practices often lead to difficulties in cooperating. With these constraints, the involvement of the EU in large-scale projects might be necessary to get projects off the ground.

Next is the impact on land use when implementing these measures. A lot of functions can also be combined. Some require a lot of space, and current functions might have to give way to support a more sustainable future. But for the restoration of nature, sometimes functions have to give room. The restoration of nature then provides more buffers for times of drought and will help the remaining functions to sustain during these hardships. And create a more stable economic basis.

Lastly, the impact of groundwater. A lot of measures involve the recharge of groundwater or aquifers. These measures can have consequences for horticultural functions in the surrounding areas when crops cannot cope with wet soils and might have severe implications for farmers. But optional would be implementing different crops that function well under these circumstances. Implementing these measures is still crucial to farmers, as water availability is also essential for farmers in drought.

Transferability

This project aims to create a pattern catalogue that contains drought-mitigating patterns that are nature-based. These patterns are set up in a more general way but then have been tested on areas along the Rhine. This pattern catalogue and the accompanying data set are transferable to other projects because every step of the decision-making for what patterns are applicable can easily be recreated and implemented elsewhere. The existing catalogue can be tested on new locations to enhance, and filtering the patterns can be fine-tuned. By trying this on other study areas, results may differ.

This pattern catalogue works for different design scales. This means it applies to many different design locations and can give insights into the best drought-mitigating measures. This multiscalar approach makes this project more transferable. –

Further research

During the research for Every Drop Counts, some other disciplines were researched. Concepts like Ecological connectivity, crop rotation, and agricultural farming with drought-resistant plants were explored, but these would require more detailed plans.

The question for water usage is also still an estimate as data was unavailable and, if available, hard to process. This part would require more information and insights from a water expert.

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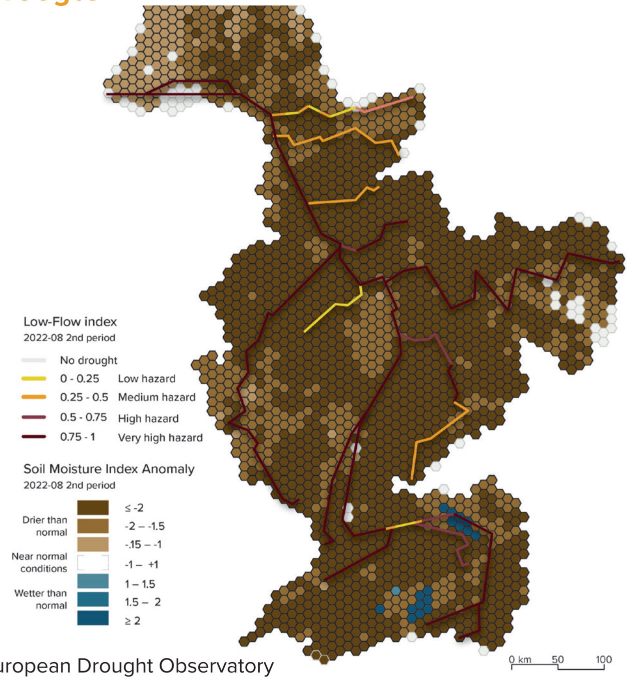
APPENDIX

Droogte



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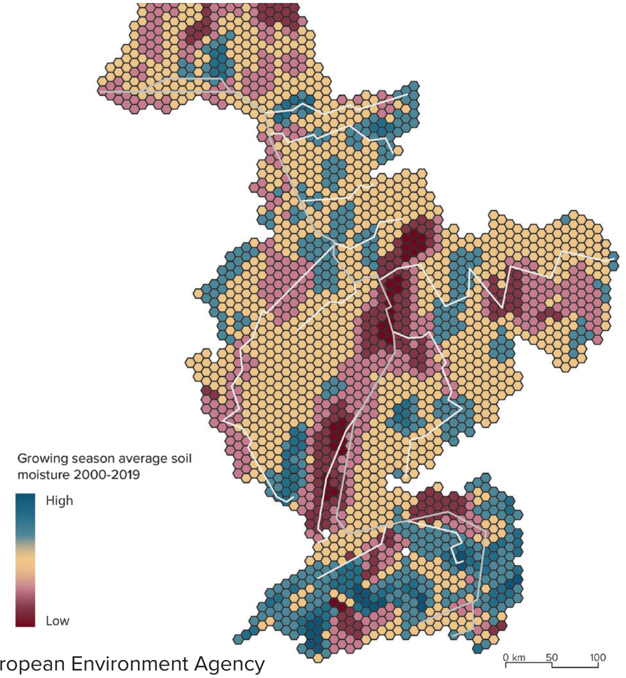

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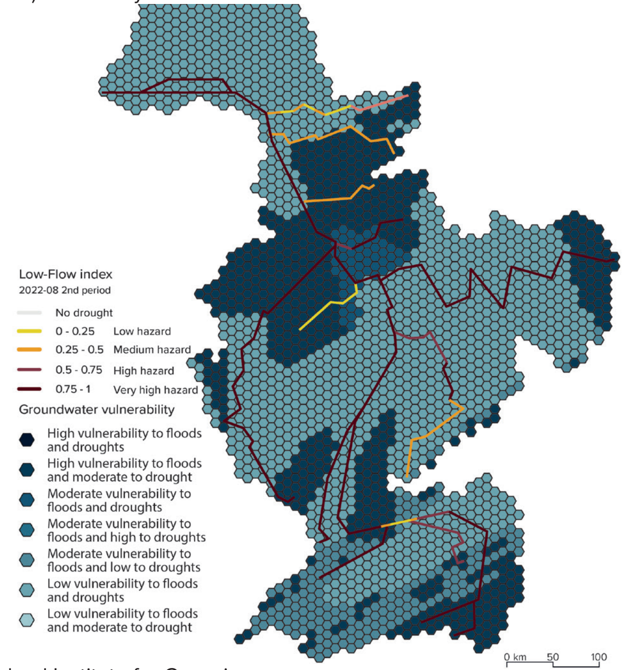

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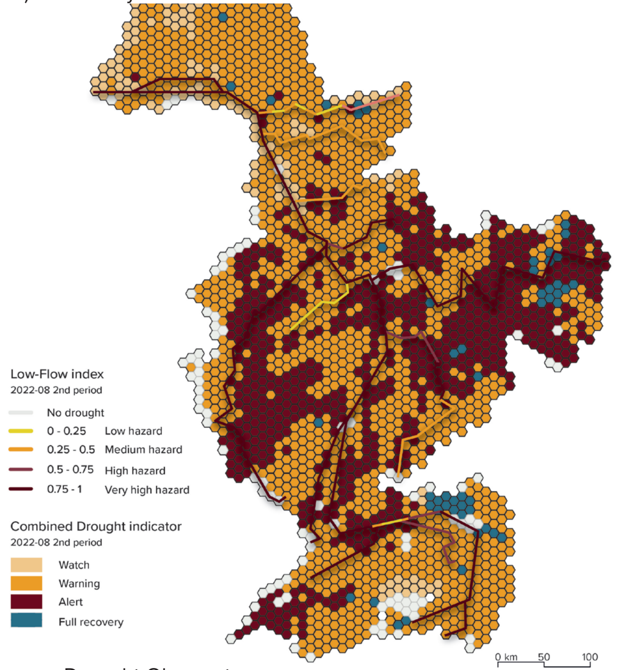

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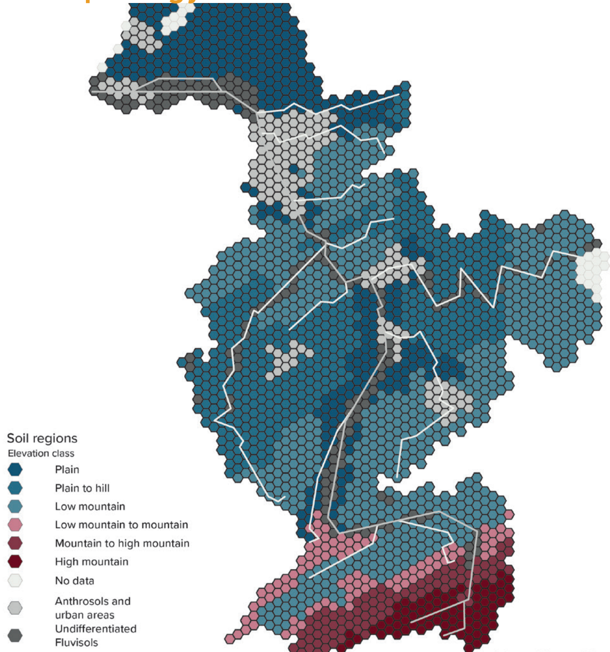

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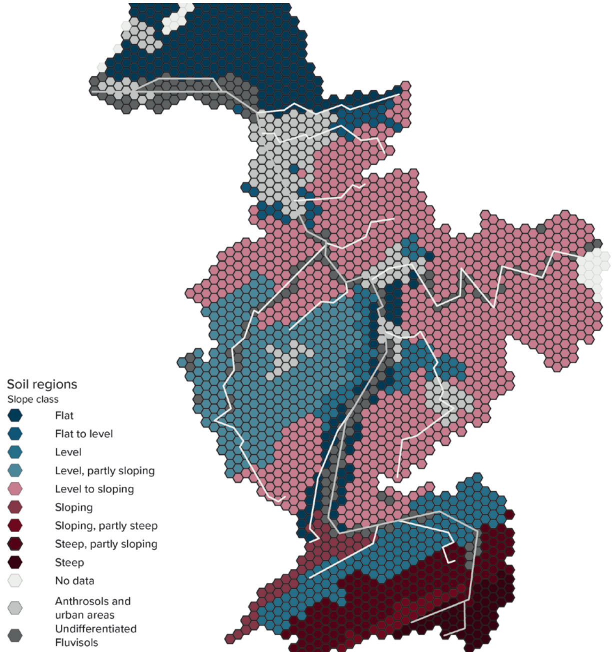

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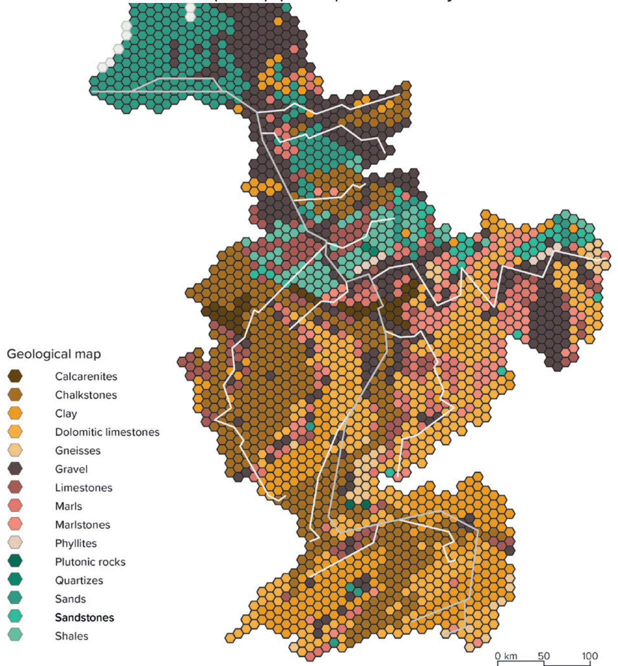

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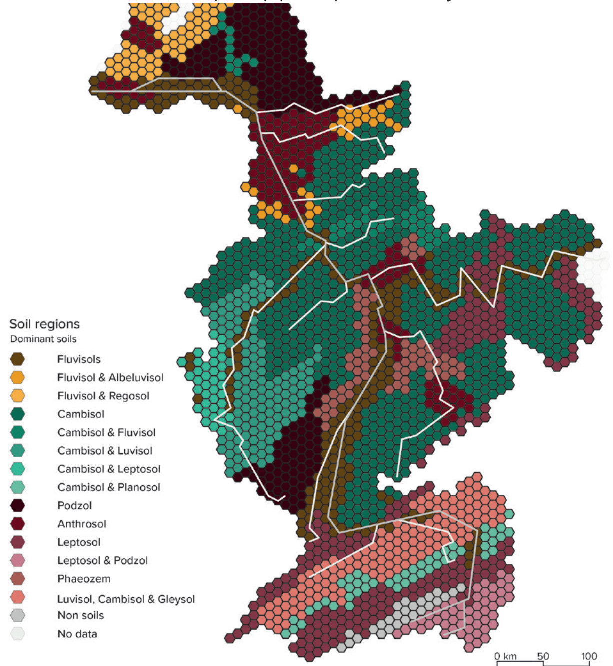

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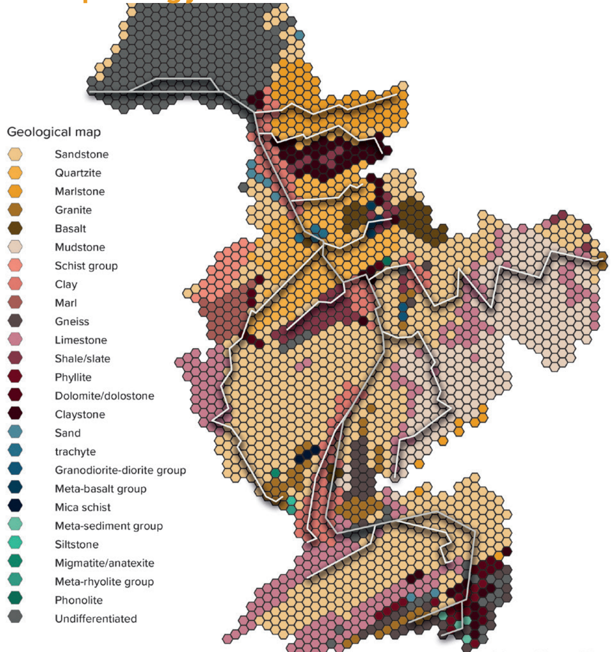

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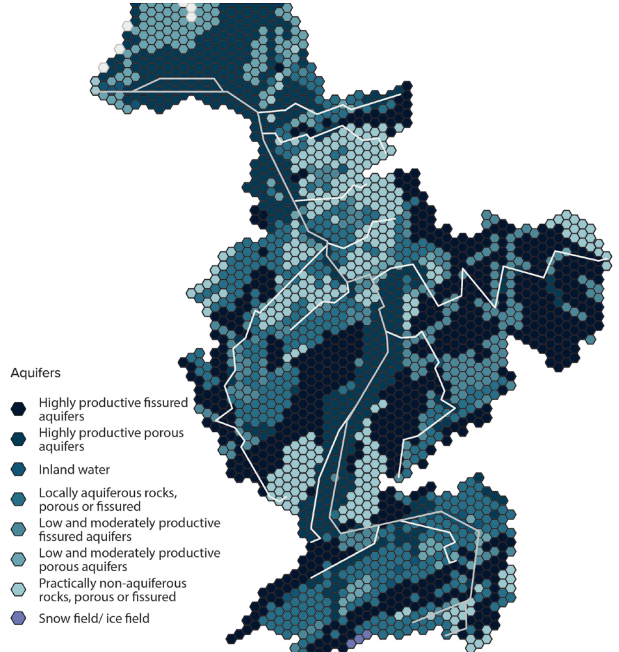

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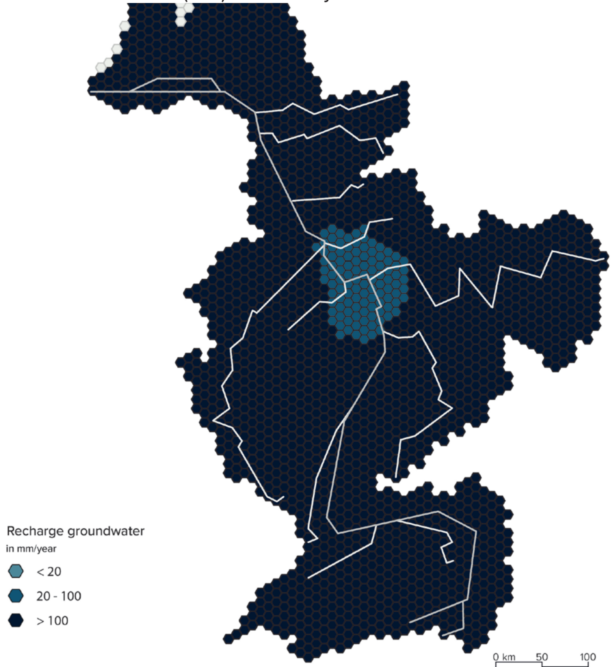

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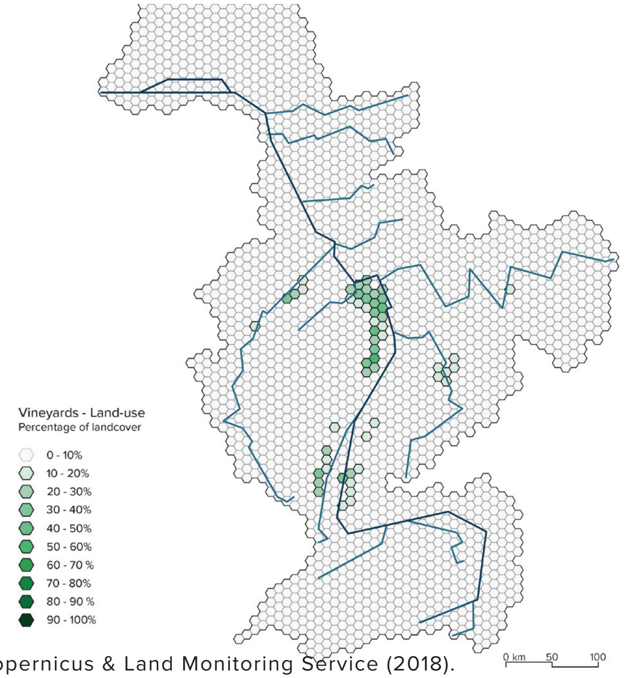

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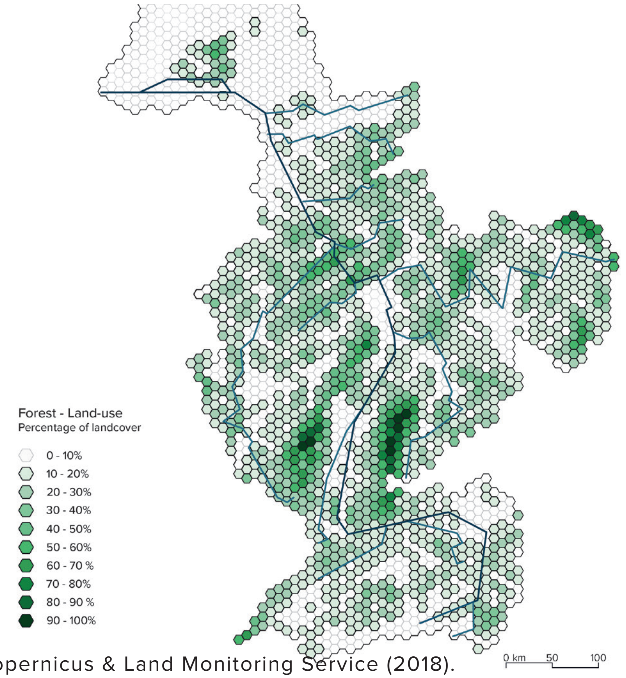

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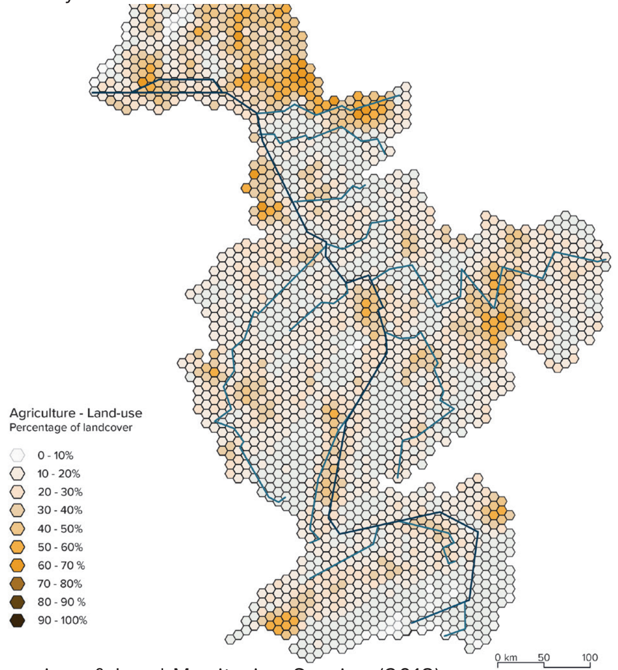

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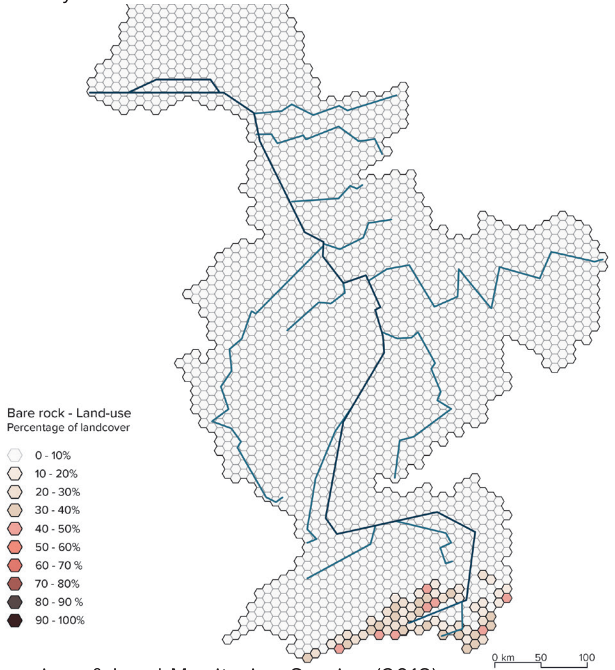

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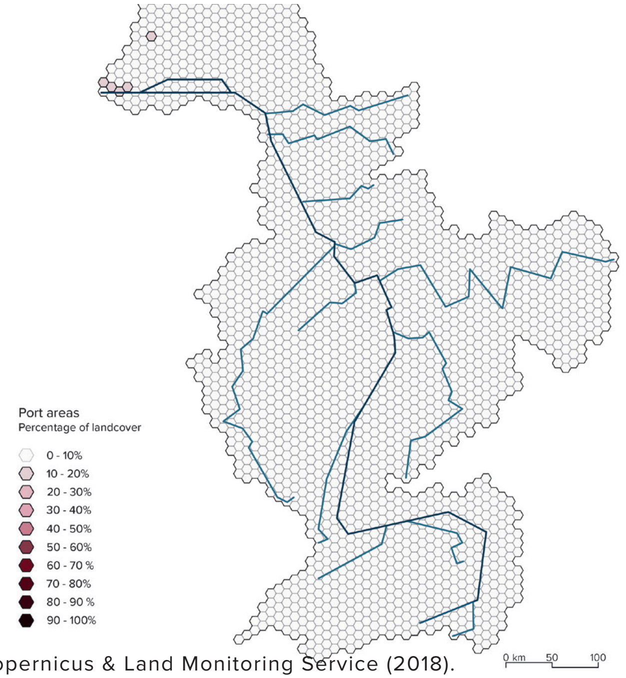
Land use & Functions



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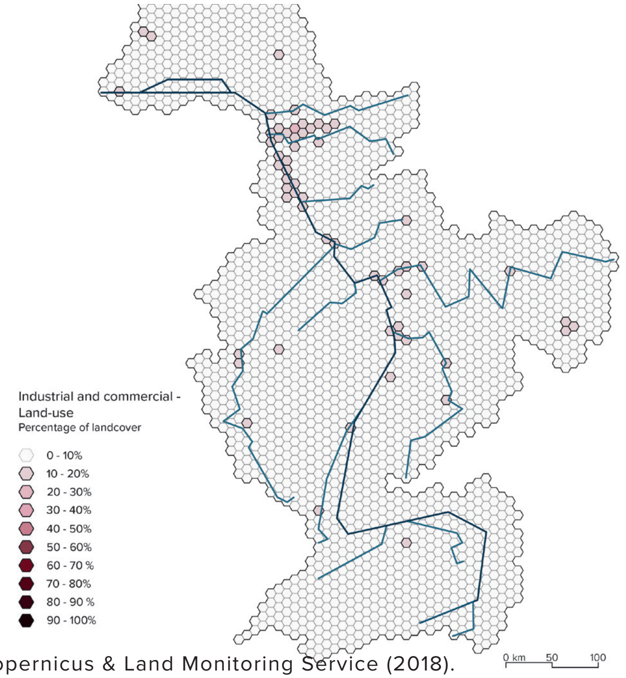

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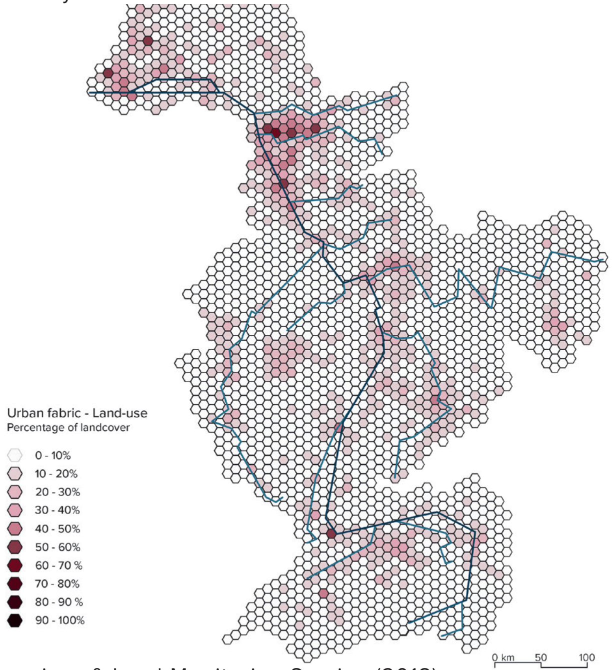

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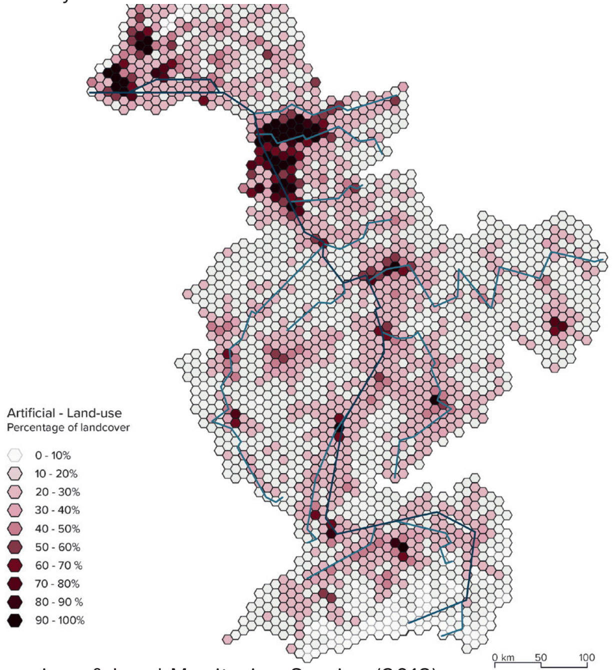

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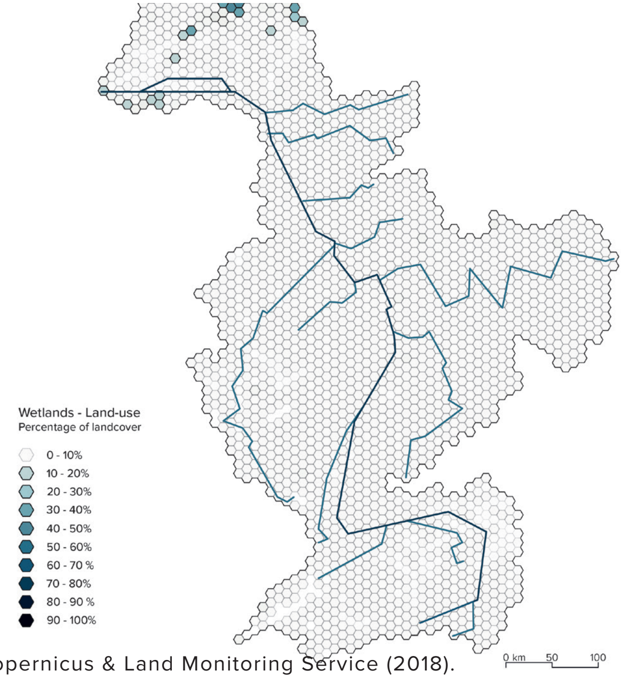
Land use & Functions



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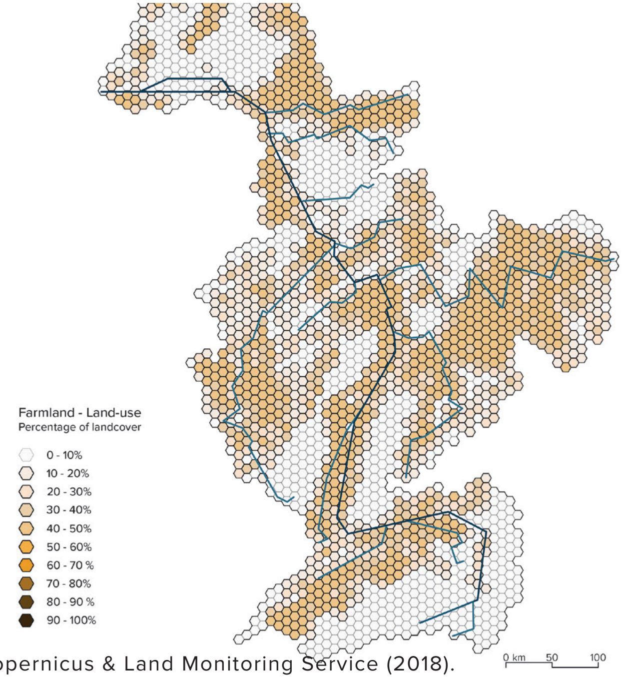

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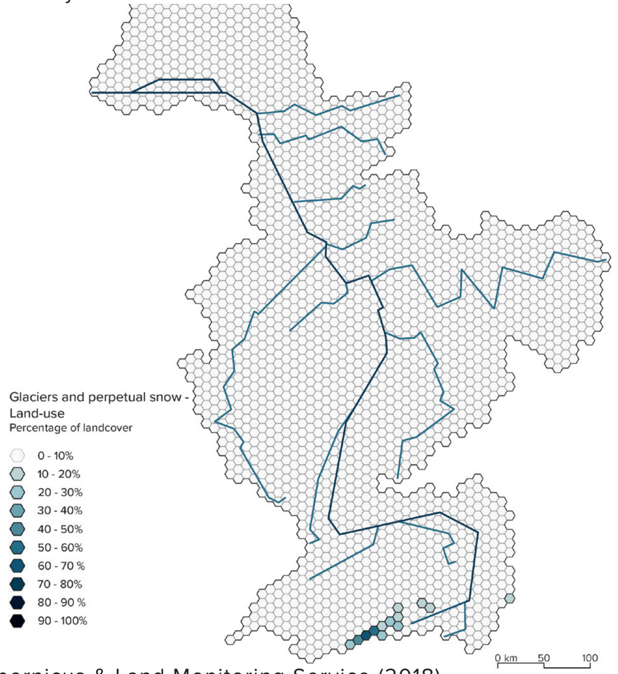

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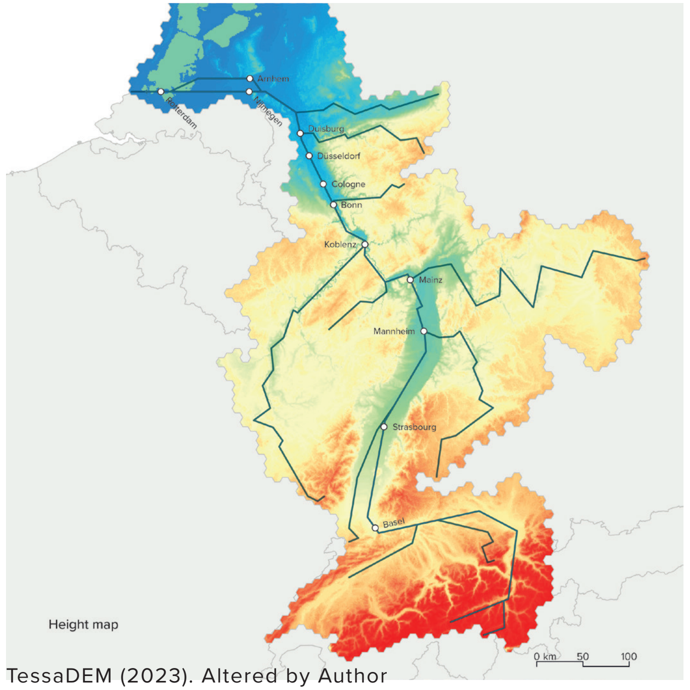

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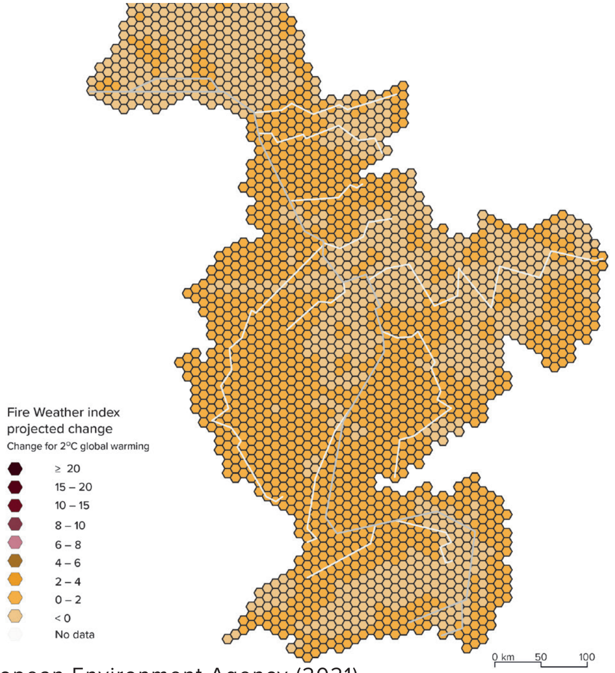

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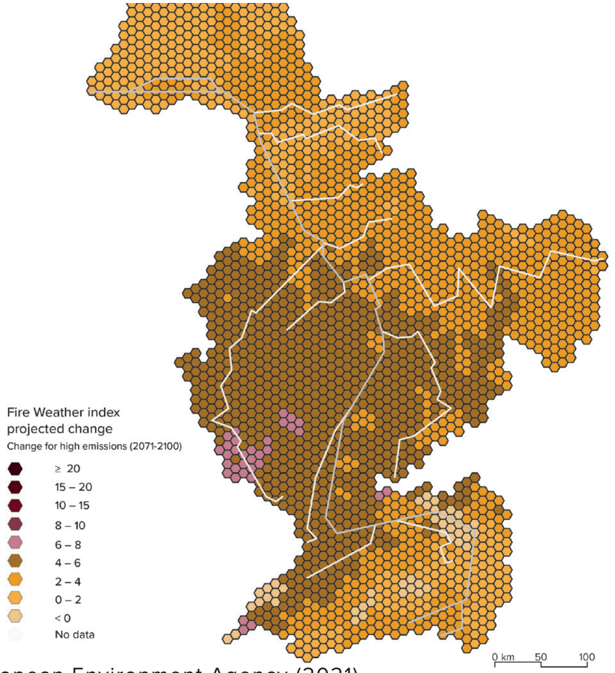

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