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Extreme Safety Predictions
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Dealing with Uncertainties
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COMPARTMENT DIKE
CANAL DIKE
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Emmerich
Rees
Xanten
Duisburg South
Dusseldorf
Koln
Bonn
Mainz
Ludwigshafen
Karlsruhe
Strasbourg
Basel
Vaduz
Oberalp
THE RHINE LINE
A. Protective Dike Character
B. Distributive Dike Character
A. Safety Failure Mechanisms
B. Water Distribution Failure Mechanisms
C. Water Retention Function
D. Water Distribution Function
Technical Dike Profiles
A. Form of the Dikes
B. Location Placement
C. Scalar Dike Impact
D. Dike Bodies Up & Down Stream
Spatial Dike Form
1.0
0.5
1.25
0.75
1.25
1.0
1.25
1.25
0.75
1.5
"The higher the change of safety failure mechanisms to take place, the lower the possibility of local autonomy"
Low risk
High risk
"The higher the potential for water to be distributed, conform the safety failure mechanism, the higher the possibility for local autonomy"
High potential
Low potential
"The higher the water retaining of a dike is classified, the lower the possibility for local autonomy"
Low retention
High retention
"The higher functional character of a dike as a distributor of water, the lower the possibility for autonomy"
Low distribution
High distribution
Scalar Interpretation
Dike Typologies
Dike Locations
Translation of Data
Translation of the 6 main safety failure mechanisms of Lola Landscape Architects (2014). Based on the probability these safety faiure mechsnisms take place according to the current dike typologies of the Rhine.
Translation of the possibilties that arise from the safety failure mechanisms based around their functional relation to water distribution, indicating the dike to have potential to function as a transitional element rather than a protective element.
Translation of the interpretation based around the functional characteristics of the dike typologies to retain the forces of the river and to protect adjacent urban functions.
Translation of the interpretation based around the functional characteristics of the dike typologies to distribute water to other locations besides the main course of the river.
75%
100%
High impact
AUTONOMY INDICATORS

Dikes can lose their water-retaining function based on safety failure mechanisms. As each dike typology consists of a different functional composition, material, mass, and height, certain dike typologies are more prone to failure mechanisms.

Although failure mechanisms are considered to decrease the stability of dikes, they also create additional features. If the water-retaining function is lowered, controlled failure mechanisms could be used to enhance the local autonomy of water distribution.

The main function of a dike is to retain the river within its boundaries. The larger the water retaining function of a dike is, the smaller the room for error becomes, lowering its localized autonomy.

Besides the main function of the dike to protect low-lying areas from high water levels, it also enhances the distribution of water. On local levels, dikes could be used to control water flows to areas of need, increasing potential autonomy.

Finding Common Water
Empowering localized autonomy of dike management for an adaptive Rhine River.

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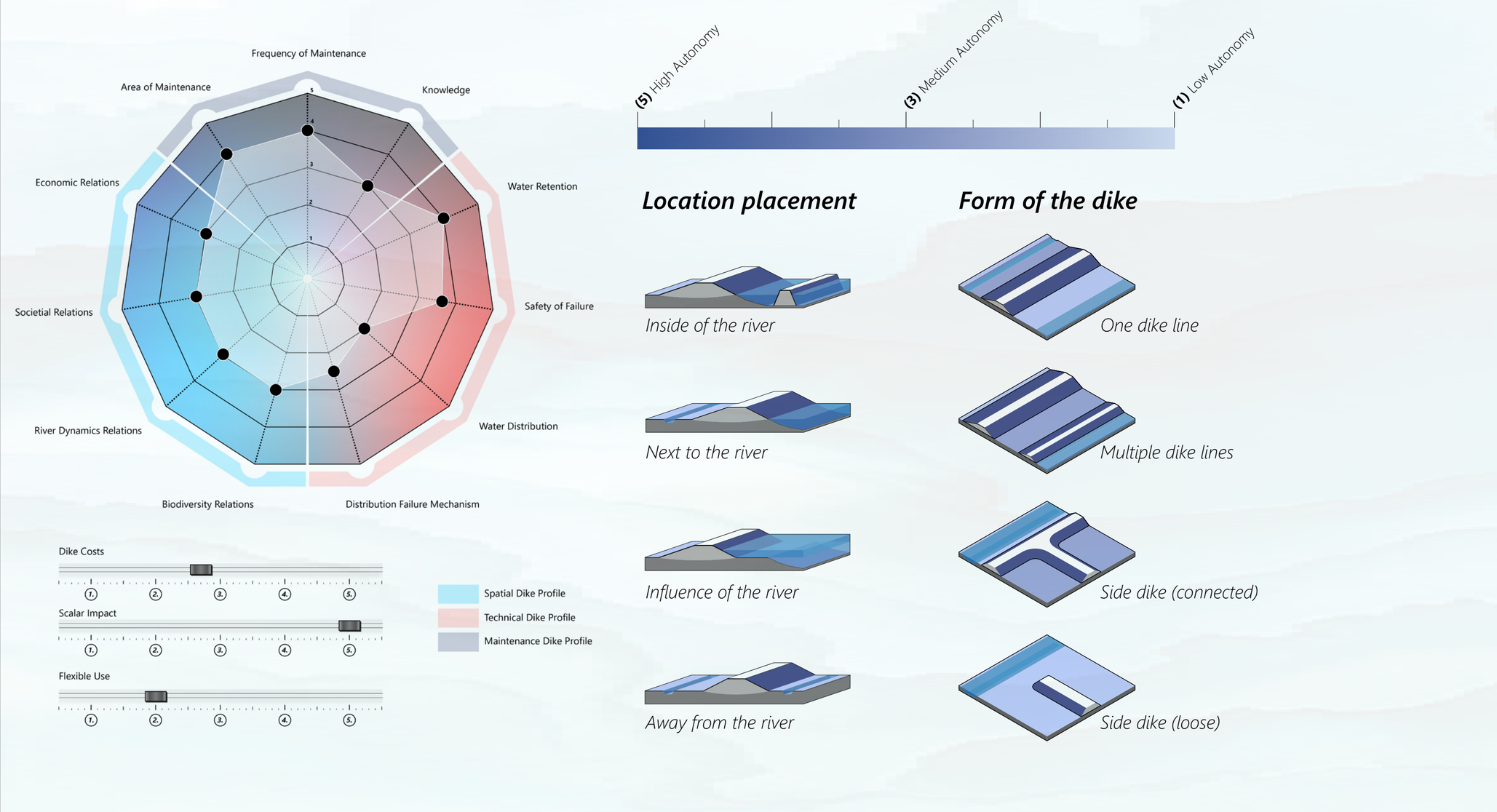

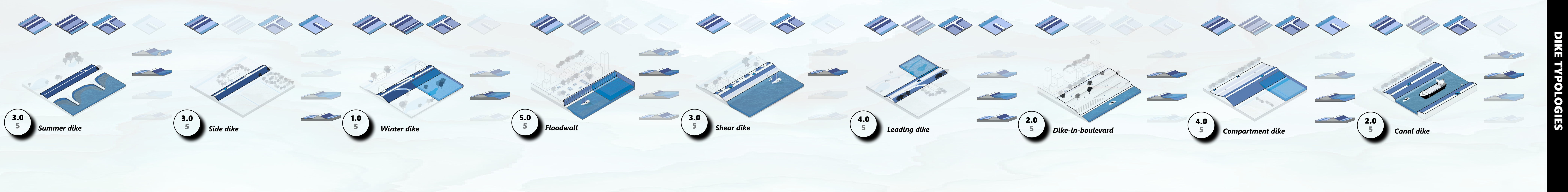

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Change in High-Low Flow (2050) | Uncertainty in High-Low Flow (2100) | Low Flow Drought | Quantitative Water Discharge | Water Distribution Mechanisms | River Hierarchy | River Measurements | Groins of the Rhine | Sedimentation Materials | River Angles & Erosion Patterns

Lithological Depositions | Soil Moisture Levels | Soil Sealing | Groundwater Recharge | Aquifer Conductivity | Aquifer Vulnerability | Extreme Flood Scenarios | Metrological Drought (Summer) | Metrological Drought (Winter) | Surrounding Water Bodies | Slope Indications | Effective Precipitation

THE RHINE LINE

DIKE CONSTRUCTION

SPATIAL DIKE PROFILES

MAINTENANCE DIKE PROFILES

RIVER DISCHARGE

AUTONOMY INDICATORS

A. *Materials for Dike Construction*

Materials for Dike Construction 1.75

Weight in (sub)calculation: 0% 25% 50% 75% 100%

Rule of Autonomy: "The higher the costs of the materials needed to construct and/or maintain a dike line, the lower the possibility for autonomy" (Low costs – High costs)

Scalar Interpretation: **Dike Typologies**

Translation of Data: Translation of the possibilities that arise from the safety failure mechanisms based around their functional relation to water distribution, indicating the dike to have potential to function as a transitional element rather than a protective element.

Dikes are primarily constructed out of a sand core with an outer protective layer of clay (Lola Landscape Architects, 2014). Although sand and clay are relatively easy to come by, specific classifications are often required (Fugro, 2012). Also, particular materials such as concrete, asphalt, or stones increase the costs of dike construction.

A. *Spatial Relations to Biodiversity*

Impact on Biodiversity 0.75

Weight in (sub)calculation: 0% 25% 50% 75% 100%

Rule of Autonomy: "The higher the intergration of biodiversity as part of the dike line, the higher the possibility for local autonomy" (High biodiversity – Low biodiversity)

Scalar Interpretation: **Dike Typologies**

Translation of Data: Translation of the interpretation based around the spatial characteristics of the dike typologies to integrate biodiversity within its spatial dike profile

Besides the protective function of a dike, dikes also facilitate green infrastructure. As dikes are often based near floodplains, this enhances the biodiversity of the river. If a lower water-retaining function and more space in the floodplain are accepted, increased levels of autonomy can be reached.

B. *Spatial Relations to River Flow*

Impact on River flow 1.25

Weight in (sub)calculation: 0% 25% 50% 75% 100%

Rule of Autonomy: "The higher the impact a dike has to change the river flow, the lower the possibility for local autonomy" (Low impact – High impact)

Scalar Interpretation: **Dike Typologies**

Translation of Data: Translation of the interpretation based around the spatial characteristics of the dike typologies to change the course and impact of the river flow on its direct surroundings.

The placement and the inclination of the dike towards the river indicate how a dike acts to the flow of the river. Dike typologies having a gentle angle towards the river, stabilize the river flow throughout the year, leading to higher potentials for autonomy.

C. *Spatial Relations to Society*

Impact on Society 1.0

Weight in (sub)calculation: 0% 25% 50% 75% 100%

Rule of Autonomy: "The stronger the relationship is between the local residents and the dike line, the higher the possibility for local autonomy" (High relevance – Low relevance)

Scalar Interpretation: **Dike Typologies**

Translation of Data: Translation of the interpretation based around the spatial characteristics of the dike typologies to determine the importance of the dike line in relationship to its residents. Often based on the historical relevance of the dike.

As dikes have been local constructions throughout history, they have been an integral part of societal life. Certain dike typologies are predominantly integrated into existing flood management practices, leading to higher acceptance by society.

D. *Spatial Relations to Economy*

Impact on Economy 0.5

Weight in (sub)calculation: 0% 25% 50% 75% 100%

Rule of Autonomy: "The higher the potential economic returns can be made from construction of a dike, the higher the possibility for local autonomy" (High returns – Low returns)

Scalar Interpretation: **Dike Typologies**

Translation of Data: Translation of the interpretation based around the spatial characteristics of the dike typologies to increase the potential economic returns of the direct surroundings.

Dikes are considered to be a heavy financial expense (Waterschap Rivierenland, 2019). New technologies considering the multifunctional and delta dikes of the Rengers & Hofmeijer (2019), could see urban functions integrated into dike lines enabling financial benefits.

E. *Land Use Flexibility*

Flexible Usage 1.5

Weight in (sub)calculation: 0% 25% 50% 75% 100%

Rule of Autonomy: "The higher the possibility for a dike line to be used within different contexts and/or landuses, the higher the possibility for local autonomy" (High flexibility – Low flexibility)

Scalar Interpretation: **Dike Typologies**

Translation of Data: Translation of the interpretation based around the spatial characteristics of the dike typologies to be used in different contexts and/or land uses. Therefore increasing the possibility of a dike typology to easier implemented than others.

Dikes can be applied in different contexts and within different land uses. Some dikes are considered to be more specialized (for example: compartment dike), whilst others can be applied on any given location (for example: floodwall). Higher flexible deployment of dike increases the carrying capacity of local stakeholders.

Spatial Dike Profiles

Spatial Dike Profiles 1.0

Weight in (sub)calculation: 0% 25% 50% 75% 100%

Rule of Autonomy: "The better a dike can be integrated into a multitude of contexts and uses, the higher the possibilities for autonomy" (High integration – Low integration)

Scalar Interpretation: **Dike Typologies**

Translation of Data: Calculation: 0.75*(Biodiversity impact) + 1.25*(River flow impact) + 1.0*(Societal impact) + 0.5*(Economic impact) + 1.5*(Flexible usage) / 5.0

A. *Area of the Protection Zone*

Area of Protection Zone 1.25

Weight in (sub)calculation: 0% 25% 50% 75% 100%

Rule of Autonomy: "The larger the overall protection zone of a dike is, the lower the possibility for local autonomy" (Low protection zone – High protection zone)

Scalar Interpretation: **Dike Typologies**

Translation of Data: Translation of the interpretation based around the spatial characteristics of the dike typologies to indicate the total area of the protection zone that needs to be maintained in order to retain its original shape and functionality

A dike consists of two maintenance regions: The area of the dike that forms the structural base of the dike (inner protection zone) and the directly related area that is under the direct influence of the dike (outer protection zone). Together these two form the Area of Protection, which needs to retain its original function.

B. *Frequency of Maintenance*

Frequency of Maintenance 0.5

Weight in (sub)calculation: 0% 25% 50% 75% 100%

Rule of Autonomy: "The higher the frequency of the maintenance needed to retain the functionality of a dike line, the lower the possibility of autonomy" (Low frequency – High frequency)

Scalar Interpretation: **Dike Locations**

Translation of Data: Translation of the interpretation based around the management characteristics of the dike typologies that indicate the frequency of maintenance. A higher amount of maintenance is needed when a dike line has a high impact on the protection of the surroundings and/or easier looses its functional purpose.

Dike maintenance occurs in two separate ways: daily maintenance (which considers monitoring, grass maintenance, and cleaning) and heavy maintenance (which takes place when certain dike bodies are deemed to have failed current safety and/or integral stability regulations and should therefore be strengthened).

C. *Knowledge of Maintenance*

Knowledge of Maintenance 0.75

Weight in (sub)calculation: 0% 25% 50% 75% 100%

Rule of Autonomy: "The higher the degree of knowledge to maintain a dike line, the lower the possibility for local autonomy" (Low knowledge – High knowledge)

Scalar Interpretation: **Dike Typologies**

Translation of Data: Translation of the interpretation based around the management characteristics of the dike typologies that indicate the degree of knowledge that is needed to maintain a dike line. As new technologies improve the protective function of the dike line, it can only be constructed by the authorities where this knowledge originates from

As dike typologies consist of different safety regulations, spatial impacts, and materials knowledge needed to maintain a dike differs. Whereas large concrete dikes are often maintained by specialized companies, grass dikes can be maintained by local farmers and other stakeholders.

Maintenance Dike Profiles

Maintenance Dike Profiles 1.0

Weight in (sub)calculation: 0% 25% 50% 75% 100%

Rule of Autonomy: "The higher the maintenance needed to retain the original function of the dike, the lower the possibility for local autonomy" (Low maintenance – High maintenance)

Scalar Interpretation: **Dike Typologies**

Translation of Data: Calculation: 1.25*(Area of Protection zone) + 0.5*(Frequency maintenance) + 0.75*(Knowledge of maintenance) / 2.5

Dike Autonomy

Dike Autonomy 1.0

Weight in (sub)calculation: 0% 25% 50% 75% 100%

Rule of Autonomy: "The higher the spatial and technical impact created by the dike, the lower the possibilities for local autonomy" (Low discharge – High discharge)

Scalar Interpretation: **Dike Typologies**

Translation of Data: Calculation: (1.5*(Spatial Dike Form) + 1.25*(Technical Dike Profiles) + 1.0*(Spatial Dike Profiles) + 1.0*(Maintenance Dike Profiles) + 0.5*(Dike cost Implications)) / 5.25 + 0.5*(Rhine riverbanks) + 0.75*(Dike systems)

A. *Change in High-Low Flow (Now-2050)*

Change in High-Low Flow (2050) 1.5

Weight in (sub)calculation: 0% 25% 50% 75% 100%

Rule of Autonomy: "The higher the change in high-low flow of the river discharge of the Rhine, the lower the possibility for local autonomy" (Low change rate – High change rate)

Scalar Interpretation: **Rhine Line**

Translation of Data: Translation of the research provided by the Stahl et al., (2022) surrounding projections of river discharge of the Rhine till 2050. Calculation was made to conduct the change rate of high (W=1) & low flow (W=1) from 2020 till 2050. Additional indictions were provided based on the relations between the change of high and low flow to each other (W=0.25). Calculation was run as per 1x4 km location along the Rhine.

To assess the impact of high and low flow on a dike, discharge numbers have been translated showing the change between projections. The results indicate that the delta and lower Rhine regions (A1) experience a higher change rate compared to the upstream areas (A2).

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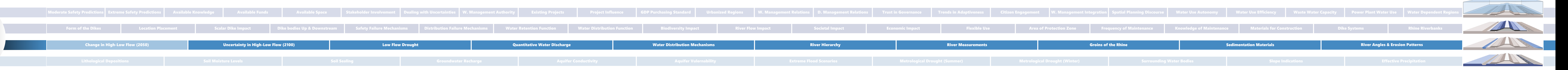
SUBCALCULATION



THE RHINE LINE

RIVER DISCHARGE

DIKE SYSTEM INTERRUPTIONS

SEDIMENTATION PATTERNS

AUTONOMY INDICATORS

B. *Change in High-Low Flow (2050-2100)*

Change in High-Low Flow (2100) — 1.0

Weight in (sub)calculation

Rule of Autonomy

"The higher the change in high-low flow of the river discharge of the Rhine, the lower the possibility for local autonomy"

Low change rate — High change rate

Scalar Interpretation: **Rhine Line**

Translation of Data

Translation of the research provided by the Stahl et al., (2022) surrounding projections of river discharge of the Rhine till 2050. Calculation was made to conduct the change rate of high (W=1) & low flow (W=1) from 2050 till 2100. Additional indictions were provided based on the relations between the change of high and low flow to each other (W=0.25). Calculation was run as per 1x4 km location along the Rhine.

This analysis focuses on the changes between 2050 and 2100, which are considered crucial for understanding the uncertainties in discharge projections. While the lower regions of the Rhine show an increased change rate (B1), the area near Mainz intriguingly exhibits a slower change rate than in 2050. This phenomenon could be attributed to the presence of large wetland areas near Oppenheim (B2).

C. *Low Flow Drought Conditions*

Low Flow Drought — 1.25

Weight in (sub)calculation

Rule of Autonomy

"The higher the degree of low flow from the year of 2022, the lower the possibility for local autonomy"

Low degree — High degree

Scalar Interpretation: **Rhine river**

Translation of Data

Translation of the information provided by the European Drought Observatory for the recent drought year of 2022 (Cammaller et al., 2021). Translated based on the difference in hydrological seasons: Winter (W=1) & Summer (W=1.25). Low flow indirectly destabilizes the structural integrity of the dike line as a constant moisture level is needed.

Low-flow drought's impact on the river is often underestimated when considering dikes. Periods of low flow can lead to the drying out of the dike, compromising its structural integrity. The area of Koblenz was particularly affected by the low flow drought of 2022 (C1), where the narrowing of the river near Kaub formed a bottleneck in the river system. However, other areas remained functional (C2).

D. *Quantitative Water Discharge*

Quantitative Water Discharge — 0.75

Weight in (sub)calculation

Rule of Autonomy

"The higher the quantitative amount of water discharge along the Rhine and water nodes, the lower the possibility for local autonomy"

Low discharge — High discharge

Scalar Interpretation: **Point data**

Translation of Data

Calculation:

1.0*(Total Discharge of Rhine) + 1.25*(Rate of Discharge Change) + 0.25*(Tributaries of the Rhine)

This section provides existing discharge data for the rivers of the Rhine basin. The higher the river's discharge, the more pressure it can exert on the dike. This is especially relevant near Koblenz, Basel, and Mader, where you find large tributaries (Moselle, Aare, and Ill).

River Discharge

River Discharge — 1.5

Weight in (sub)calculation

Rule of Autonomy

"The higher the future changes in river discharge as per high & low flow content, the lower the possibility for local autonomy"

Low discharge — High discharge

Scalar Interpretation: **Rhine river**

Translation of Data

Calculation:

1.5*(Change High-Low 2050) + 1.0*(Change High-Low 2100) + 1.25*(Low flow drought) + 1.0*(Quantitative discharge) / 4.75

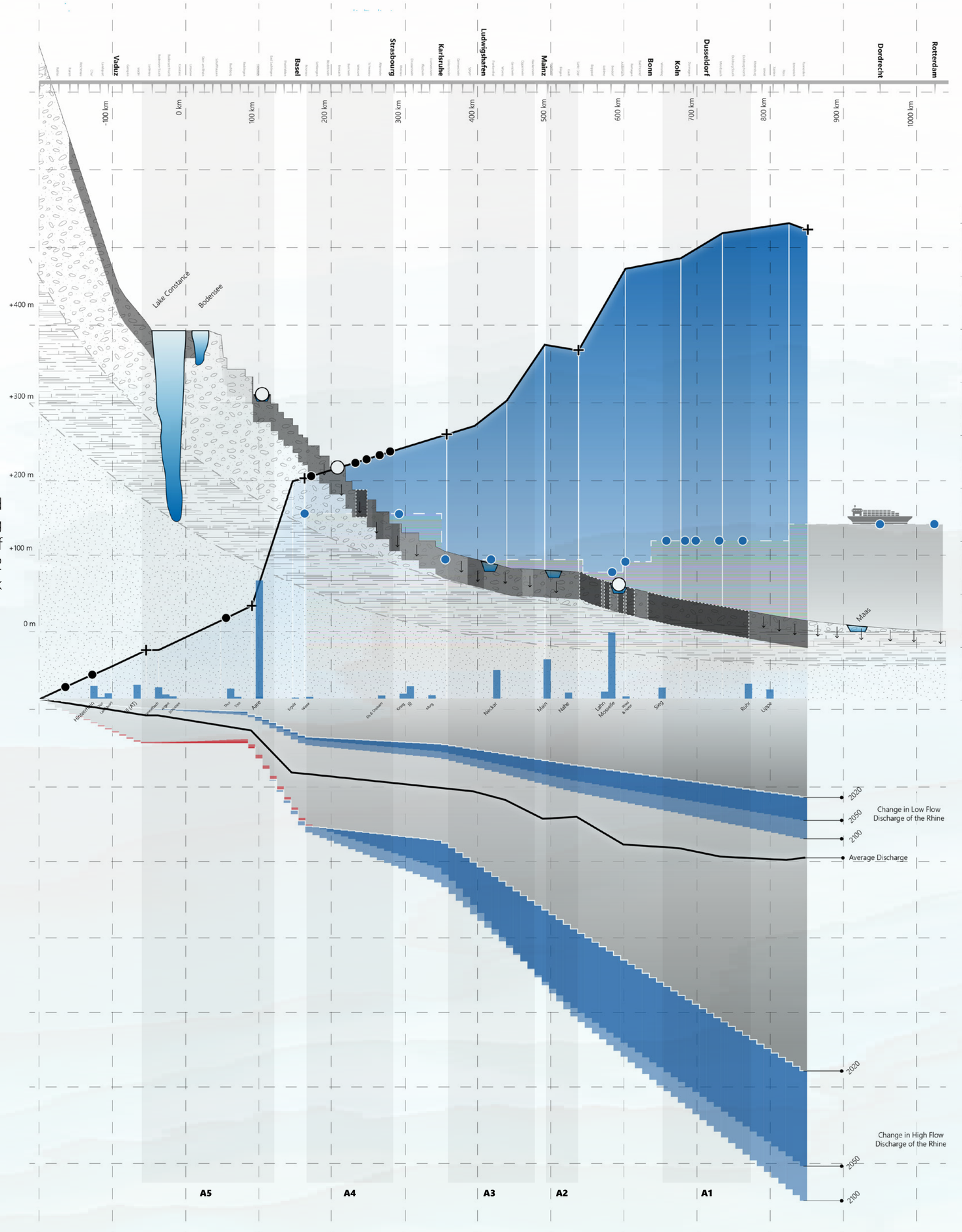


Figure: Rhine section with river discharge related information.

A. *Water Distribution Mechanisms*

Water Distribution Mechanisms — 1.0

Weight in (sub)calculation

Rule of Autonomy

"The higher the amount fo water distribution mechanisms along the river, the lower the possibility for local autonomy"

Low amount — High amount

Scalar Interpretation: **Point data**

Translation of Data

Translation of the data provided by AMBER Consortium (2020), the water distribution mechanisms of culverts (+0.25), sluices (-0.75), Weirs (-1) and dams were mapped within the 10km boundary set along the Rhine. The usage of these instruments primairly results in a change of the river flow increasing the pressures on dike lines

Distribution mechanisms are primarily considered technical applications to control or alter the original course of the river to manage water flows. In the agricultural regions of the lower Rhine (A1), culverts are used to redistribute water flows, whereas in the areas around Strasbourg (A2), dams and weirs are employed to slow down the water flow. The latter significantly impacts the pressure on dikes.

B. *River Hierarchy*

Water Nodes — 0.75

Weight in (sub)calculation

Rule of Autonomy

"The higher the classifcation of thre tributaries of the Rhine based on their Strahler levels, the lower the possibility for local autonomy"

Low degree — High degree

Scalar Interpretation: **Point data**

Translation of Data

Translation of the Strahler classifications of river hierarchies, indicating the importance of the river to the overall water system. Based on the information provided by the Copernicus (2019). Translation was made within the 1x4 km line raster. Indications of higher rivers on the hierachial sclae indicates the importance of that river body, needing dike lines to be able tomore structurally sound.

Stahler's classifications address the river's importance within the hierarchical water system (Copernicus, 2019). The Rhine is classified as the highest hierarchical river, with tributaries like the Moselle (B1), the Aare (B3), and the Main (B2) as the largest secondary rivers. A higher classification indicates potentially more intense pressure on the dikes.

C. *River Measurements*

River Measurements — 0.5

Weight in (sub)calculation

Rule of Autonomy

"The wider the river flows, the larger constant pressure is put on the adjacent dike lines, the lower the possibility for local autonomy"

Low width — High width

Scalar Interpretation: **Rhine river**

Translation of Data

Translation of the information provided by Allen and Pavelsky (2018) indictating the median river width of the river based on respective river segments of the Rhine.

The river's width is used to assess the load balance of the river regarding its surroundings. A wider river can generate more water pressure on the adjacent area. This is evident in the section between Bingen and Mainz (C1), where the narrowing of the Rhine Gorge at Kaub increases the river's width upstream.

D. *Groins of the Rhine*

Groins of the Rhine — 1.0

Weight in (sub)calculation

Rule of Autonomy

"The stronger the respresentation of groins along the Rhine, the higher the possibility for local autonomy"

High respresentation — Low representation

Scalar Interpretation: **Point data**

Translation of Data

Translation of empirical data mapping the available groin location along the Rhine within the 1x4 km raster of the line. Representation was measured based on the percentage filled of groins per location. 100%: +1, 75%: +0.75, 50%: +0.5 & 25%: +0.25. Availability of groins reliefs water pressure from the dike lines.

Groins are water distribution mechanisms often found in lower-lying regions (D1 + D2), where the river has more space. Groins are constructed within the river to relieve dike pressures and maintain navigability. However, while they reduce pressure locally, they increase streamflow, which can have impacts downstream.

Dike System Interruptions

Dike System Interruptions — 0.75

Weight in (sub)calculation

Rule of Autonomy

"The higher the amount anomolies along the river, the lower the possibilities for local autonomy"

Low anomolies — High anomolies

Scalar Interpretation: **Point data**

Translation of Data

Calculation:

(1.0*(Water distribution mechanisms) + 0.75*(Water Nodes) + 0.5*(River Measurements)) / 3.75 + (1.0*(Groins))

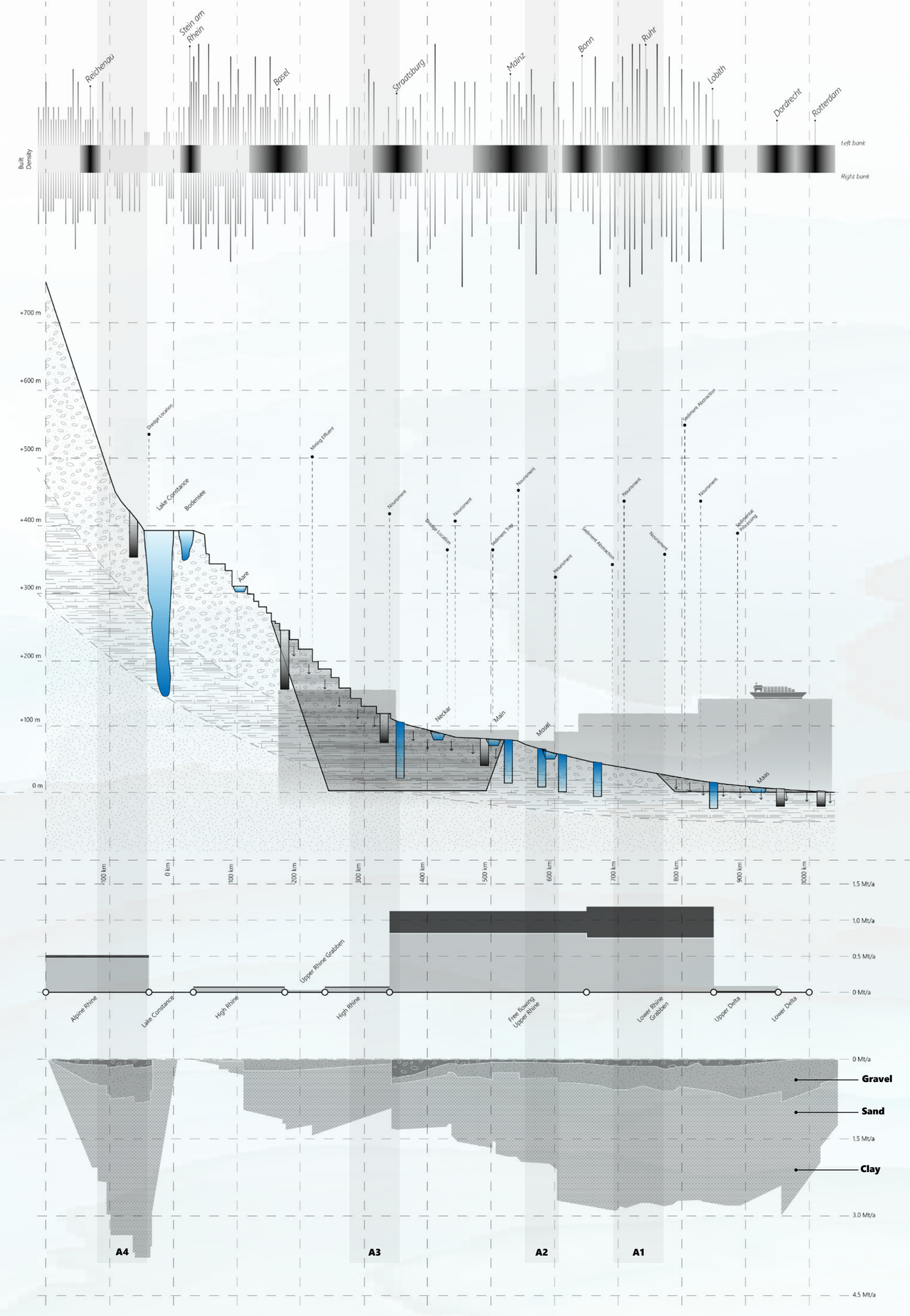


Figure: Rhine section showing existing Sedimentation Patterns.

A. *Sedimentation Material*

Sedimentation Material — 1.25

Weight in (sub)calculation

Rule of Autonomy

"The higher the amount of sediments deposited on location, the higher the possibility for local autonomy"

High amount — Low amount

Scalar Interpretation: **Rhine Line**

Translation of Data

Translation of the information provided by Frings, et al (2019) indicating the deposition of sedimentation material along the Rhine based on the materials of clay (W=2), sand (W=1.5) & gravel (W=1). Indications of sedimentation locations along the Rhine indirectly relief dike pressures and form a material base for construction.

The types of sediment provide insights into the river's dynamics. Sediment is categorized into three main groups: Clay, Sand, and Gravel. These sediments deposit at varying speeds, impacting local river flow. Sedimentation can create a secondary protective layer near the dike and may also serve as material for dike construction. However, the accumulation of sediment within the river, can lead to blockages and increased water pressure upstream.

B. *Sedimentation & Erosion*

River Angles & Erosion — 1.5

Weight in (sub)calculation

Rule of Autonomy

"The higher the degree of the angle within the course flow of the Rhine, the higher the possibility for local autonomy"

High biodiversity — Low biodiversity

Scalar Interpretation: **Rhine Line**

Translation of Data

Translation of empirical information of the course flow of the Rhine. Calculation was conducted by connecting the points of the river based on a 4km length, making it transferable for the 1x4 km Rhine line. Th lower the angle of the river becomes, the more speed is facilitated, leading to higher process of erosion ath the feet of the dike

As the river bend angle increases, the speed of the river flow rises, leading to the erosion of the outer bank. This can compromise the structural integrity of dike, as the dike's toe may erode. Locations with large river meanders are near Dusseldorf (B1), the Rhine gorge area (B2), the High Rhine between Basel and Konstanz (B4), and near the Rhine source in the Oberalppass (B5).

Sedimentation Patterns

Sedimentation Patterns — 1.25

Weight in (sub)calculation

River Dynamics

Dynamics Conditions — 1.0

Weight in (sub)calculation

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River Discharge

Legend

Sedimentation Patterns

Legend

SUBCALCULATION

THE RHINE LINE

SOIL CONDITIONS | GROUNDWATER CONDITIONS | FLOODING & DROUGHT | ADDITIONAL

AUTONOMY INDICATORS

A. Lithological Depositions
Weight: 0.75

"The higher the suitability of the underlying lithological depositions for dike construction (stability+ material), the higher the possibility of local autonomy"

High suitability — Low suitability

Scalar Interpretation: **Shapefile Areas**

Translation of Data: Translation of the information provided by the BGR (2019) on the Lithological depositions of Europe. Based on the characteristics of the underying formations and their translation for dike stability and a potential source for dike materials.

Lithological depositions indicate the underlying geomorphological conditions where a dike can be constructed. Since dikes are primarily built using sand and clay, they are best suited to areas with similar sediment deposits, as found in the lower floodplains of the lower Rhine (A1), the Upper Rhine Valley (A2), and the Alpine Rhine Valley (A3).

B. Soil Moisture
Weight: 1.25

"The lower the soil moisture index indicates as per hydrological season, the lower the possibility for autonomy"

High soil moisture — Low soil moisture

Scalar Interpretation: **Raster (11.1x11.1 km)**

Translation of Data: Translation of the information provided by the European Drought Observatory for the recent drought year of 2022 (Cammalleri et al., 2016). Translated based on the difference in hydrological seasons: Winter (W=1) & Summer (W=1.5). Low soil moisture rates indicate potential threats for the structural integrity of the dike concerning drought

Dikes are often located near rivers where soil moisture levels tend to be high. Given that dikes are integral parts of water systems for seepage and drainage purposes, high soil moisture levels are required. On the contrary, in the region between Basel and Breisach before the major hydro dams, low soil moisture levels have been detected (B2).

C. Soil Sealing
Weight: 1.0

"The higher the level of the soil that is sealed by concreate and other stone objects, the lower the possibility for autonomy"

Low sealing rate — High sealing rate

Scalar Interpretation: **Land Use Classifactions**

Translation of Data: Translation of the information provided by the land use classifications of Corine Land cover (Copernicus, 2018) concerning the impermirability rate as per classified land use unit. As dikes need to be part of the surrounding water system to retain its structural integrity, a low permability rate decreases the suitability of dike construction

As dikes are primarily constructed from clay and sand, they need to be placed directly on open soil to ensure the integration of force fields. Soil sealing also affects drought and flood possibilities as little infiltration and evaporation of water is detected. Therefore, these locations are primarily found near urbanized regions such as the Ruhr (C1), Ludwigshafen (C2), and Basel (C3).

Soil Conditions
Weight: 1.5

"The higher the conditions of the soil suitable for dike construction, the higher the possibility for local autonomy"

High suitability — Low suitability

Scalar Interpretation: **Rhine Basin**

Translation of Data: Calculation: 0.75*(Lithological depositions) + 1.25*(Soil moisture) + 1.0*(Soil Sealing) / 3

A. Groundwater Recharge
Weight: 1.5

"The higher the amount of groundwater to be recharged within the underlying aquifers (mm/year), the higher the possibility for autonomy"

High recharge — Low recharge

Scalar Interpretation: **Raster (1x1 km)**

Translation of Data: Translation of the data provided by GEUS (2021) on the potential groundwater recharge from 1960-2010. A high degree of recharge indicates the suitability of the soils to collect and transport water flows increasing the drainage capacity and saturation levels needed for dikes

High groundwater recharge indicates favourable ground conditions, allowing water to infiltrate naturally (GEUS, 2021). This relieves water pressures within the dike. This is primarily the case in the Alpine regions of the Rhine (A1).

B. Aquifer Conductivity
Weight: 0.75

"The higher the conductivity of the underlying aquifers, the higher the possibility for local autonomy"

High conductivity — Low conductivity

Scalar Interpretation: **Shapefile Areas**

Translation of Data: Translation of the information provided by the BGR (2019) on the aquiferal conductivity of Europe. High conductivity rates increase the rate for water to be infiltrated by the subsoil water tables, increasing the drainage and saturation rates needed for dikes

The increasing porosity of aquifers indicates the productivity of an aquifer, reflecting the movement of water within. The higher the aquifer conductivity of an area, the better the conditions for dike construction, as it allows water to be distributed more quickly. This is seen in lower-lying regions (B1 & B2), where the lithological soils facilitate water infiltration into aquifers relatively close to the subsurface.

C. Aquifer Vulnerability
Weight: 1.0

"The higher the vulnerability of the aquifers of the Rhine, the lower the possibility for local autonomy"

Low vulnerabilities — High vulnerabilities

Scalar Interpretation: **Shapefile Areas**

Translation of Data: Translation of the information provided by BGR (2015) on the vulnerabilities of the aquifers of Europe. Calculation is provided based on the risk evaluation on the potentials of flooding and drought of aquifers (High (1), Moderate (3), Low (5))

In addition to current aquifer conditions, aquifers are also affected by the negative impacts of climate change, posing threats such as flooding or drying out of the soil. This can significantly affect the structural integrity of a dike. Areas between Mainz and Kaub are considered susceptible to both drought and floods (C1). Areas near Basel and Vaduz are more prone to flooding.

Groundwater Conditions
Weight: 1.0

"The stronger the effectiveness of the groundwater conditions, the higher the possibility for local autonomy"

High effectiveness — Low effectiveness

Scalar Interpretation: **Rhine Basin**

Translation of Data: Calculation: 1.5*(Groundwater recharge) + 0.75*(Aquifer conductivity) + 1.0*(Aquifer vulnerability) / 3.25

A. Extreme Flooding Scenario
Weight: 2.0

"The higher the extend of riverine flood risk based on the most extreme scenario, the lower the possibility for local autonomy"

Low risk — High risk

Scalar Interpretation: **Shapefile Areas**

Translation of Data: Translation of the extreme riverine flooding scenario provided by IKSR (BAFG, 2015). Calculation of the data was made based on the depth of the flooding height: >4m (1), 2-4m (2), 0.5-2m (3), <0.5m (4) and no flooding (5)

Due to increasingly extreme climate scenarios, rivers are more prone to causing large floods. Therefore, dikes must withstand these water fluctuations. The more prone areas are located in the low-lying regions (A1 & A3). The location between Karlsruhe & Mainz (A2) is important as increased floods occur due to the canalized zone of Strasbourg.

B. Metrological Droughts (Winter)
Weight: 1.0

"The higher the degree of drought according the the drought year of 2022, the lower the possibility for local autonomy"

Low degree — High degree

Scalar Interpretation: **Raster (11.1x11.1 km)**

Translation of Data: Translation of the drought indicators for the year of 2022 provided by the European Drought Observatory (Cammalleri et al., 2021). Based on the translation of monthly drought data on the classifications of No drought (5), Watch (4), Warning (3-2), Alert (1). The indications of drought increases structural damage to the outer layer of the dike, decreasing its structural integrity

Winter metrological droughts are more common in regions with higher altitudes, where rivers rely more on glacial water than rainwater. This is why regions like the Alpine Rhine Valley (B3) and the High Rhine Hill landscape (B2) are more susceptible to drought.

C. Metrological Droughts (Summer)
Weight: 1.25

"The higher the degree of drought according the the drought year of 2022, the lower the possibility for local autonomy"

Low degree — High degree

Scalar Interpretation: **Raster (11.1x11.1 km)**

Translation of Data: Translation of the drought indicators for the year of 2022 provided by the European Drought Observatory (Cammalleri et al., 2021). Based on the translation of monthly drought data on the classifications of No drought (5), Watch (4), Warning (3-2), Alert (1). The indications of drought increases structural damage to the outer layer of the dike, decreasing its structural integrity

In the summer, metrological droughts are more common in areas dependent on rainwater. This is often observed in lower-lying regions such as the Ruhr (C1) and the Upper Rhine Valley of the canalized zone in France (C2). Drought can significantly impact dikes, potentially drying out the outer protective layer of the dike and leading to instability.

Flooding & Drought
Weight: 2.0

"The higher the impact created by flooding and/or drought, the lower the possibilities for local autonomy"

Low risk — High risk

Scalar Interpretation: **Rhine Basin**

Translation of Data: Calculation: 2.0*(Extreme flooding scenario) + 1.25*(Hydrological drought summer) + 1.0*(Hydrological drought winter) / 4.25

A. Surrounding Water Bodies
Weight: 0.25

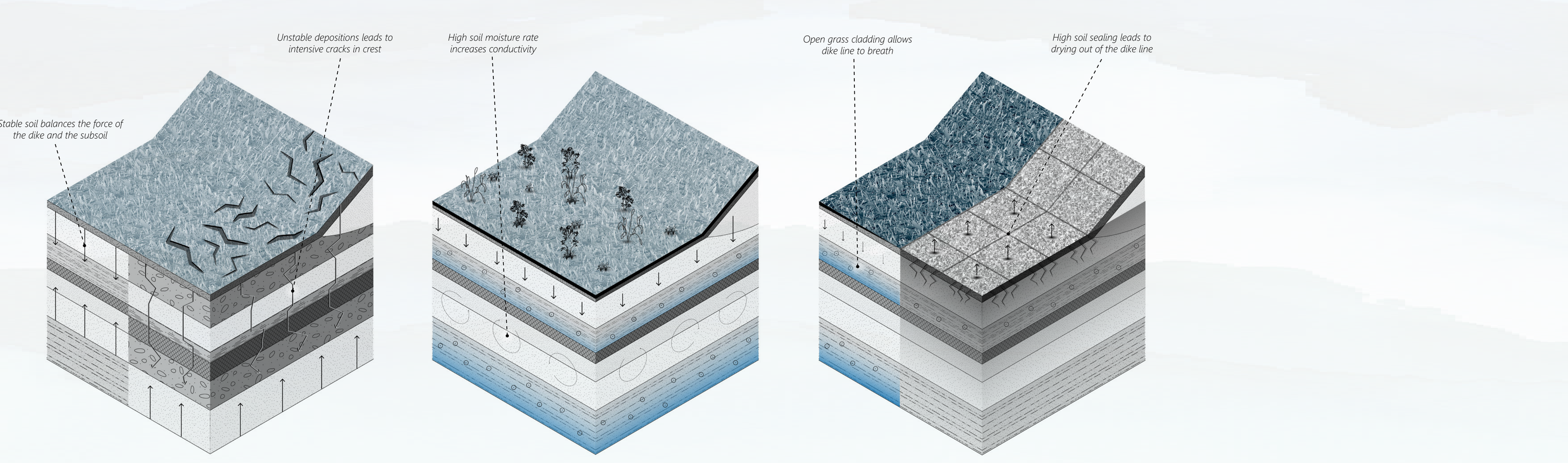
"The more adjacent water bodies occur within the 1x4 km raster, the higher the possibility for lcoal autonomy"

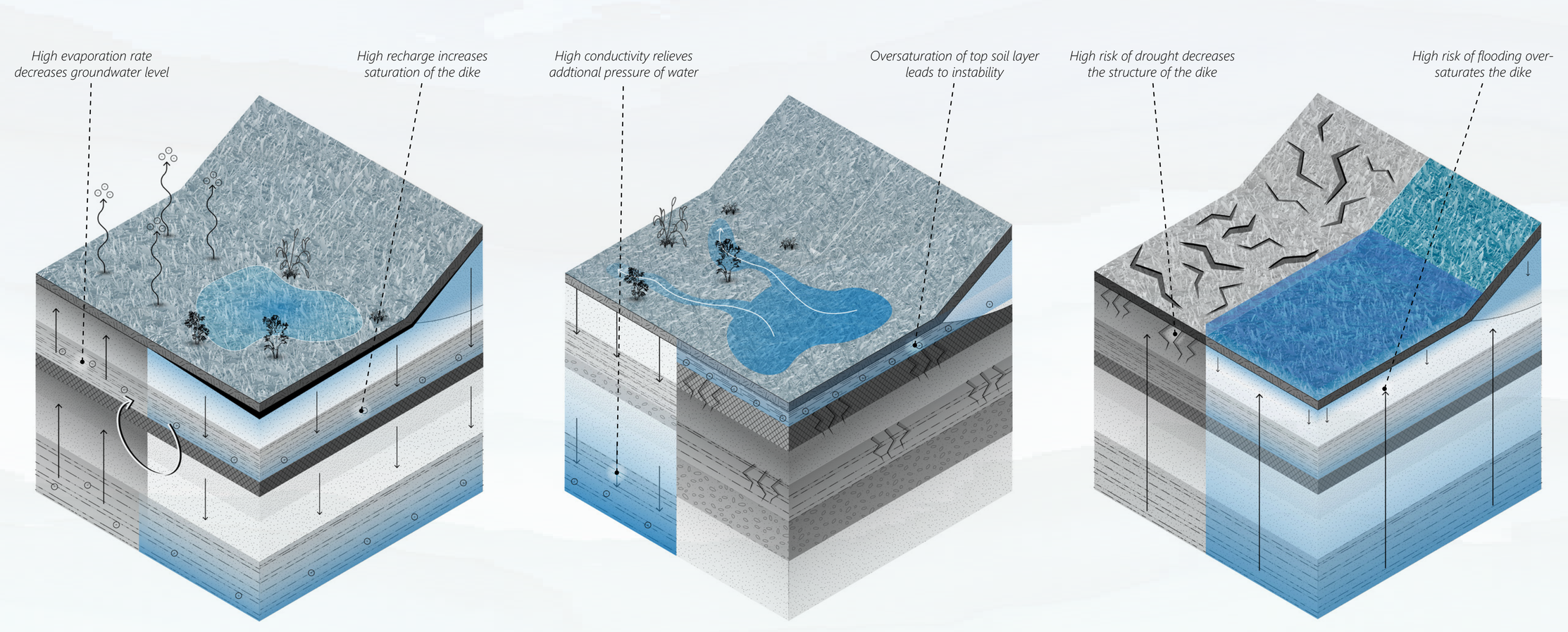
High adjacency — Low adjecency

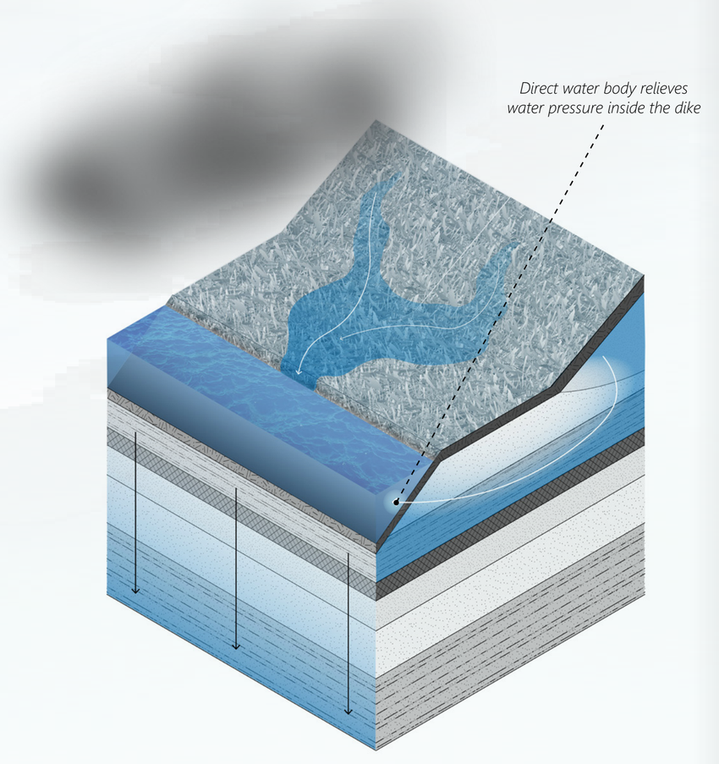
Scalar Interpretation: **Shapefile Areas**

Translation of Data: Translation of the classification provided by the Copernicus (2019) based on the types of water represented in Europe. Calculatin is made based on the translation of the types of water: Natural: 5, Reservoir: 2, Unknown: 3, Canal: 1. The suitabitlity of the construction of a dike is dependent on a source of water to relief seepage and drainage

The proximity of a dike to surrounding water bodies increases local dike management. It provides a constant water source for relieving water pressures within the dike. These regions are primarily located where water has more space, such as the lower Rhine regions with their sediment industries (A1) and the wetlands of the Upper Rhine (A2).







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November 2023

Legend

Elevation Profile in relation to Rhine River Subbasins

SUBCALCULATION

THE RHINE LINE

ADDITIONAL CONDITIONS

FLOOD SAFETY REGIONS

DECISION MAKING AUTONOMY

AUTONOMY INDICATORS

B. Slope Indications

Slope Indications A 1.0

Weight in (sub)calculation

Rule of Autonomy

"The higher the indications of the slope level based on the elevation profiles, the lower the possibility for local autonomy"

Low degree — High degree

Scalar Interpretation: **Raster (100x100m)**

Translation of Data

Translation of the elevation profiles of the Rhine to the degrees of slopes that are created. Calculation is made based on the extend of the slope suitable for dike placement: 0-2.5° (0.5), 2.5-7.5° (1.0), 7.5°+ (0). Based on the range from 0-90°. Therefore the potential lowlying regions are highlighted as they indicate the possibility to construct a dike.

Dikes are typically constructed on relatively flat surfaces. Surfaces with significant elevation differences are less prone to floods, making dike construction unnecessary. However, locations with little elevation differences can function as dikes in relatively low-lying areas, allowing for more possibilities for dike construction. This is evident in flatter regions such as the Dutch-German border (B1) and the Upper Rhine Valley (B2).

C. Effective Precipitation

Effective Precipitation 0.5

Weight in (sub)calculation

Rule of Autonomy

"The higher the effective precipitation, the hgigher the possibility for local autonomy"

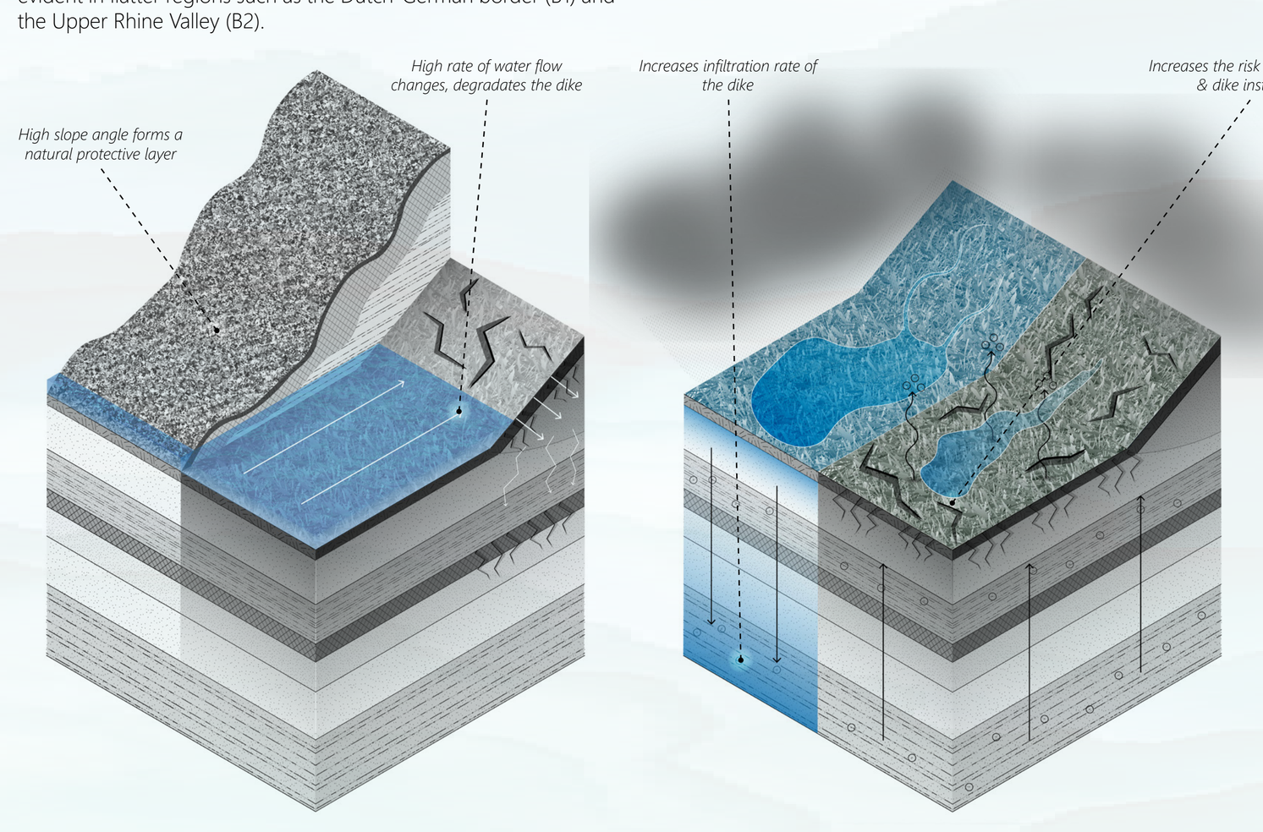
High precipitation — Low precipitation

Scalar Interpretation: **Dike Typologies**

Translation of Data

Translation of the data provided by GEUS (2021) on the effective precipitation from 1960-2010. A high degree of precipitation indicates the suitability of the soils to collect water flows increasing the saturation levels needed for dikes

Effective precipitation, like Groundwater Recharge mentioned in the previous calculation, indicates the soil's suitability for water infiltration. Here the additional component of precipitation is added. In relatively urbanized regions (C1-C3), effective precipitation tends to be lower.



Suitability Conditions

Suitability Conditions 1.0

Weight in (sub)calculation

Rule of Autonomy

"The higher the impact created by the dynamics of the river to the adjacent river banks and dikes, the lower the possibilities for local autonomy"

Low discharge — High discharge

Scalar Interpretation: **Point data**

Translation of Data

Calculation:

(1.5*(Soil Conditions) + 1.0*(Groundwater conditions) + 2.0*(Flooding & Drought) + 0.5*(Effective precipitation)) / 5 + 0.25*(Surrounding Water bodies) + 1.0*(Slope Indications)

A. Moderate Safety Predictions*

Future Prediction (Moderate) 1.0

Weight in (sub)calculation

Rule of Autonomy

"The higher the rate of change between current and moderate safety scenarios, the lower the autonomy"

Low change rate — High change rate

Scalar Interpretation: **River Basins**

Translation of Data

Difference between the dike breach probabilities of current reference data and the moderate climate scenario of RACMO (Linde et al., 2011)

Dikes are designed based on the existing flood safety regulations. However, due to climate risks, different scenarios have been developed to show future regulatory change. According to the moderate scenario of IPCC SRES A1B (Linde et al. 2011), safety regulations should be enhanced near the Dutch-German border (A1). The area of the Middle Rhine between Karlsruhe and Bonn (A2) shows a relatively lower increase.

B. Extreme Safety Predictions*

Future Prediction (Extreme) 1.0

Weight in (sub)calculation

Rule of Autonomy

"The higher the rate of change between current and moderate safety scenarios, the lower the autonomy"

Low change rate — High change rate

Scalar Interpretation: **River Basins**

Translation of Data

Difference between the dike breach probabilities of current reference data and the extreme climate scenario of WP 2.1 (Linde et al., 2011)

Based on the extreme scenario provided by Linde et al. (2011), covering a larger part of the Middle and Lower Rhine between Köln and Düsseldorf (B1), there is considered to be a lower increase in safety compared to other regions. However, the channelized zone of the Rhine between Basel and Karlsruhe (B2) now shows a significant increase.

Flood Safety Regions

Flood Safety Regions 1.0

Weight in (sub)calculation

Rule of Autonomy

"The higher the rate of change between current and future flood safety regulations, the lower the possibilities for local autonomy"

Low rate — High rate

Scalar Interpretation: **River Basins**

Translation of Data

Calculation:

1.0*(Future flood safety: Moderate) + 2.0*(Future flood safety: Extreme) / 4.25

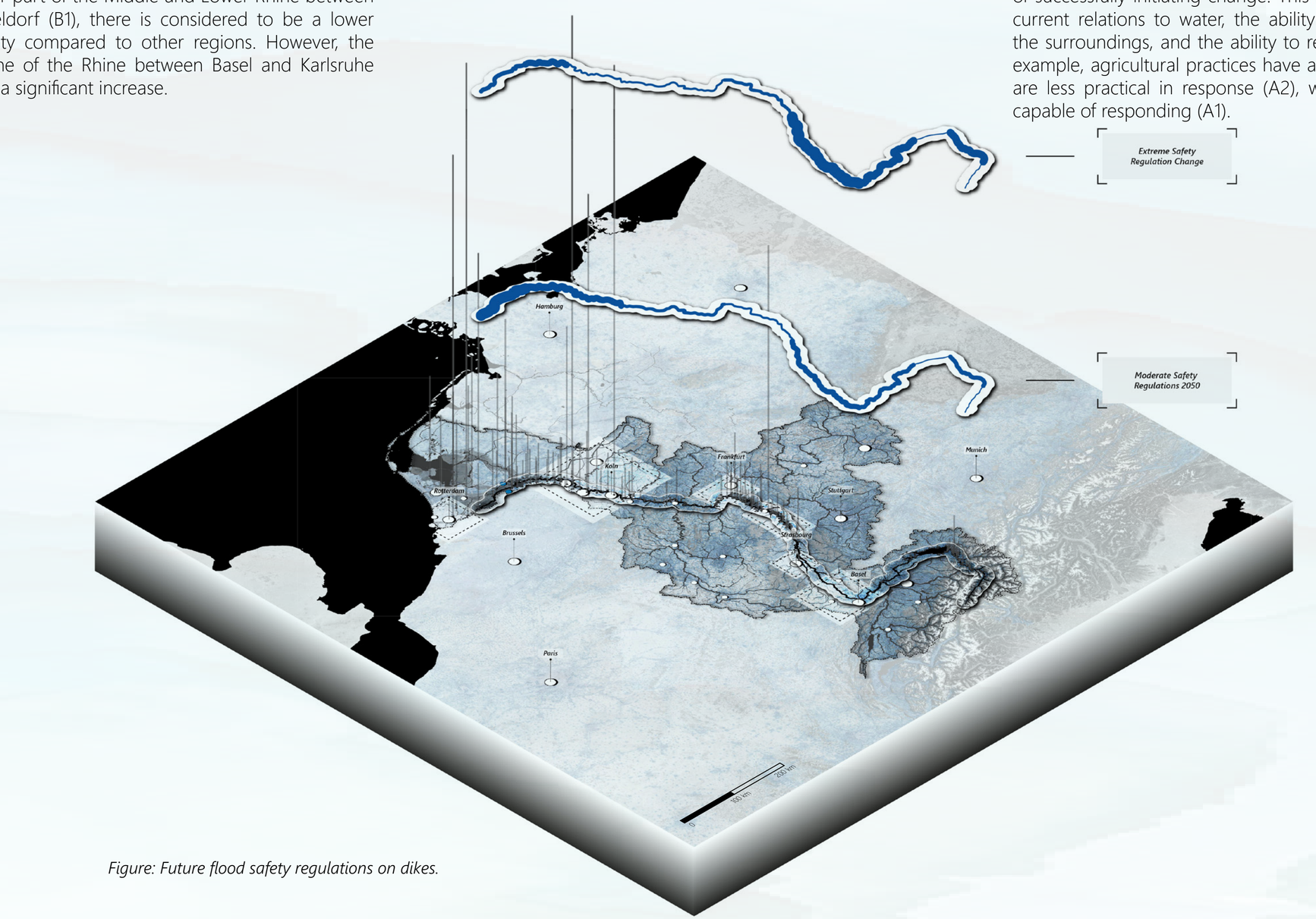


Figure: Future flood safety regulations on dikes.

A. Available Knowledge

Available Knowledge 2.0

Weight in (sub)calculation

Rule of Autonomy

"The higher the rate of knowledge available of the water & dike system, the larger the potential for local autonomy"

High knowledge rate — Low knowledge rate

Scalar Interpretation: **Land Use Classifications**

Translation of Data

Translation of knowledge availability per land use based on: Level of Knowledge (W=1), Methods & Data (W=0.75) & Adaptive Response to Change (W=0.5)

The level of knowledge present per land use explains the possibility of successfully initiating change. This is based on the indicators of current relations to water, the ability to gather information from the surroundings, and the ability to respond in times of need. For example, agricultural practices have a high level of knowledge but are less practical in response (A2), while natural areas are more capable of responding (A1).

B. Available Funds

Available Funds 1.75

Weight in (sub)calculation

Rule of Autonomy

"The higher the funds available to spend on dike management, the higher the potential for local autonomy"

High funds — Low funds

Scalar Interpretation: **Land Use Classifications**

Translation of Data

Translation of the interpretation of the availability of funds that can be dedicated to dike management as per classified land use classificaiton

Financial requirements are essential if local change is initiated. Especially for the construction of dikes (CTCN, n.d; Waterschap Riverland, 2023), a substantial financial burden is present. Due to the high urbanization rate of the industrial regions of Ruhr (B1), Ludwigshafen (B2), and Basel (B3), higher interest is dedicated to protection. Which eventually leads to larger funds to be allocated to dike management projects.

C. Available Space

Available Space 1.5

Weight in (sub)calculation

Rule of Autonomy

"The higher the available space there is to initiate change, the higher the potential for local autonomy"

High space availability — Low space availability

Scalar Interpretation: **Land Use Classifications**

Translation of Data

Translation of the interpretation of the available space per land use that can be dedicated for a change in dike management

For local dike change to be facilitated, the need of space arises. Primarily, the agricultural and natural regions of the pasture lands of the Dutch-German polders (C1) and the wetland and agricultural zones between Ludwigshafen and Mainz (C2) facility useable space for dike change, as the urbanization rate is considered to be low.

D. Stakeholder Involvment

Stakeholder Involvement 0.75

Weight in (sub)calculation

0% 25% 50% 75% 100%

Rule of Autonomy

"The higher the amount of stakeholders impacted by an initiation of change, the lower the possibility for autonomy"

Low involvement — High involvement

Scalar Interpretation: **Land Use Classifications**

Translation of Data

Translation of the interpretation of the involvement of stakeholders as per land use. Based on the Width of Participation (W=1) (amount of stakes) & Depth of Participation (W=1) (scalar importance)

Change in one location can impact direct surroundings. Therefore, when considering an initiative, the impact and the involvement of other stakeholders affects the potential for local autonomy. This impact can be seen both in terms of width and depth of involvement. It is particularly relevant in urbanized regions (D1 & D2), where higher potential impacted stakeholders are located.

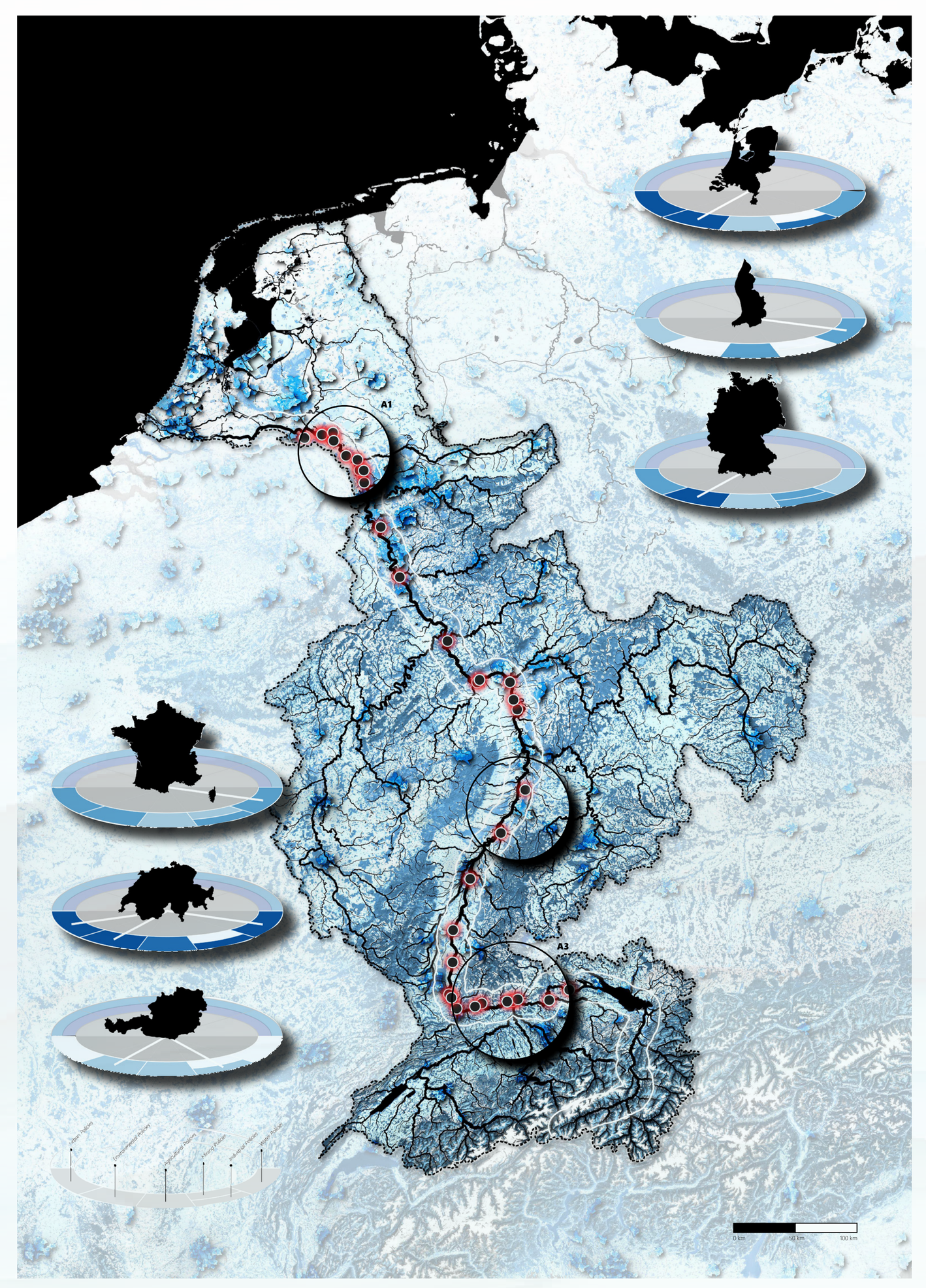


Figure: Decision-making autonomy of dike management along the Rhine.

E. Dealing with Uncertainties

Dealing with Uncertainties 0.5

Weight in (sub)calculation

Rule of Autonomy

"The higher the ability per land use to deal with uncertainties within water availability and protection levels, the higher the possibility of autonomy"

High degree of change — Low degree of Change

Scalar Interpretation: **Land Use Classifications**

Translation of Data

Translation of the interpretation of how land use related stakeholder cope with dealing with uncertainties. Based on how stakeholders consider alternatives (W=1) & Handling of uncertainty (W=1)

When initiating change, alternatives of existing practices have to be established. The willingness of change and the alternatives practices differ per stakeholder groups. Certain practices, such as the industrial sectors, which are dependent on a constant source of water (Düsseldorf: E1, Mainz: E2 & Mannheim: E3), have limited consideration of alternatives.

F. Authority in Water Management

Authority within Water Management 1.0

Weight in (sub)calculation

0% 25% 50% 75% 100%

Rule of Autonomy

"The higher the integration of sectoral policies to the local levels public authority, the higher the possibility for local autonomy"

High integration — Low integration

Scalar Interpretation: **Land Use Classifications**

Translation of Data

Translation of the authority within water management as per land use. Additional translation is made based on level of policy integration & responsible scale of authority as per national data (ESPON, 2018).

Based on the authority that different land uses have in the decision-making process of their nation-states (ESPON, 2018), existing urban land uses of the Rhine have a higher authority in water management. For example, there is a low integration of agricultural policies in the Netherlands, Germany, and Austria (F1 & F3) and a high integration of environmental policies in Germany and Switzerland (F2 & F4) (ESPON, 2018).

G. Existing Projects

Existing Projects A 0.75

Weight in (sub)calculation

Rule of Autonomy

"The availability of existing projects on location increases the availability of localized knowledge, increasing the possibility of local autonomy"

High knowledge availability — Low knowledge availability

Scalar Interpretation: **Project Areas**

Translation of Data

Translation of the type of project in relation to its usefullnes within dike management. Based on the extent of the project area (BAFG, 2015). Project focus: River (0.25), Backland (0.5), Foreland (0.75), Embankment (0.75), Dike (1.0)

Available knowledge can also be created through adjacent projects by the IKSR (BAFG, 2015). The availability of local resources, knowledge, and communication from these ongoing projects could lead to new possibilities for local actors to use available resources while retaining their autonomy within the decision-making process. The existing projects where ranked based on the relation to dike management.

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Decision-making Autonomy

Legend

Sectoral policy integration

Flood Safety Regions

Legend

SUBCALCULATION

THE RHINE LINE

AUTONOMY INDICATORS

H. *Project Influence*

"The higher the availability of knowledge related to adjacent project, the higher the possibilities for local autonomy"

High knowledge rate — Low knowledge rate

Scalar Interpretation: **Project Areas**

Translation of Data: Translation of the type of project in relation to its usefullnes within dike management. Based on the extent of the project area (BAFG, 2015). Focus: River (0.25), Backland (0.5), Foreland (0.75), Embankment (0.75), Dike (1.0)

In addition to the availability of nearby project locations, the influence of knowledge can alos be facilitated through communicative channels. Therefore, authorities related to dike and/or water management could have additional knowledge available, making it easier for local initiatives to encouraged. Here, the areas of H1, H2 (Kreise), and H3 (Canton) have a wide range of influence based on the size of the respective administrative regions.

Decision-Making Autonomy

Decision Making Autonomy — 2.0

Scalar Interpretation: **Land Use Classifications**

A. *Socio-Economic Conditions*

Socio Economic Conditions — 1.75

Scalar Interpretation: **NUTS Regions (2 & 3)**

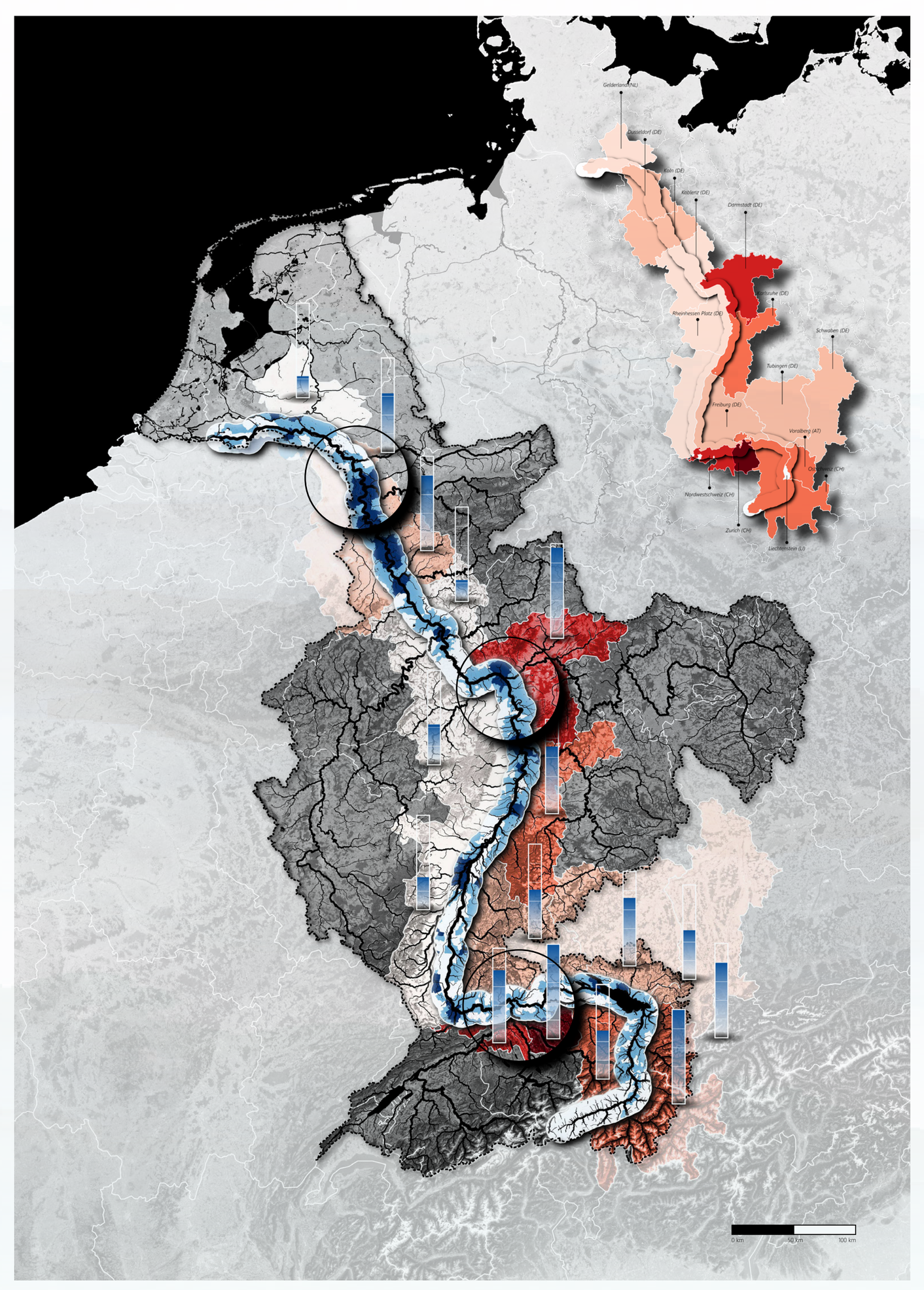

Figure: Socio-economic conditions of the Rhine basin.

B. *Political Landscape*

Political Landscape — 4.5

Scalar Interpretation: **Nation States**

Autonomy of the Administration

Autonomy of Administration — 1.5

Scalar Interpretation: **NUTS Areas**

A. *Water Use Autonomy*

Water Use — 0.75

"The higher the amount of water use per classified land use, the lower the possibility for local autonomy"

Low water use — High water use

Scalar Interpretation: **Land Use Classifications**

Translation of Data: Translation of the amount of water use per classified land use. Calculation is run based on the water use per Agricultural, Electicity Cooling, Mining and Quarrying, Public water supply & Manufacturing classifications of the EEA (2023). Additional deduction of autonomy is made based on differences between the Rhine nations.

The amount of water used per land use classification emphasizes the sector's interdependency on a stable water source. Data from the EEA (2023) regarding national statistics, categorized by sectors, reveals variations in water use across different countries. It is evident that natural areas (A2) and agricultural lands in Germany (A1 & A3) exhibit low water consumption. In contrast, French water use in the agricultural sector (A4) is notably higher, and Swiss public water use (A5) exceeds that of other nations by a significant margin.

B. *Water Use Efficiency*

Water Efficiency — 0.25

"The higher the efficiency rate of water use per classified land use, the higher the potential for local autonomy"

High efficiency — Low efficiency

Scalar Interpretation: **Land Use Classifications**

Translation of Data: Translation of the amount of water use per classified land use. Calculation is run based on the water resource efficiency rate of the Industrial, Agricultural and public service sectors per Rhine nation (Aquastat, 2023). Additional deduction of autonomy is made based on differences between the Rhine nations.

Water use efficiency refers to the adaptability of the designated land uses in terms of water resource dependency. For example, the French agricultural sector (B2) demonstrates high efficiency compared to Germany (B1). Although Germany's public and industrial water use is substantial, it is relatively more efficient than Austrian and Dutch practices.

C. *Waste Water Capacity*

Waste Water Capacity — 1.0

Weight in (sub)calculation: 0% 25% 50% 75% 100%

Rule of Autonomy: "The higher the waste water treated per resident and capacity of the facility, the lower the possibilities for autonomy"

Low treatment — High treatment

Scalar Interpretation: **Waste Treatment Facilities**

Translation of Data: Translation of the amount of waste water treated per person per day in m3 (W=1) & the overall size of the facility (designed capacity - population served) (W=0.75). Data based on the dataset provided by Ehalt et al. (2021)

The level of autonomy is determined by the size and production capacity of these treatment facilities. Notably, Swiss water facilities (C2) are less autonomous due to the relatively larger size of their plants compared to other areas along the Rhine. In contrast, smaller facilities spread out between Breisach and Mainz (C1) have more potential for local autonomy but are heavily regulated by channelized dams upstream of Strasbourg.

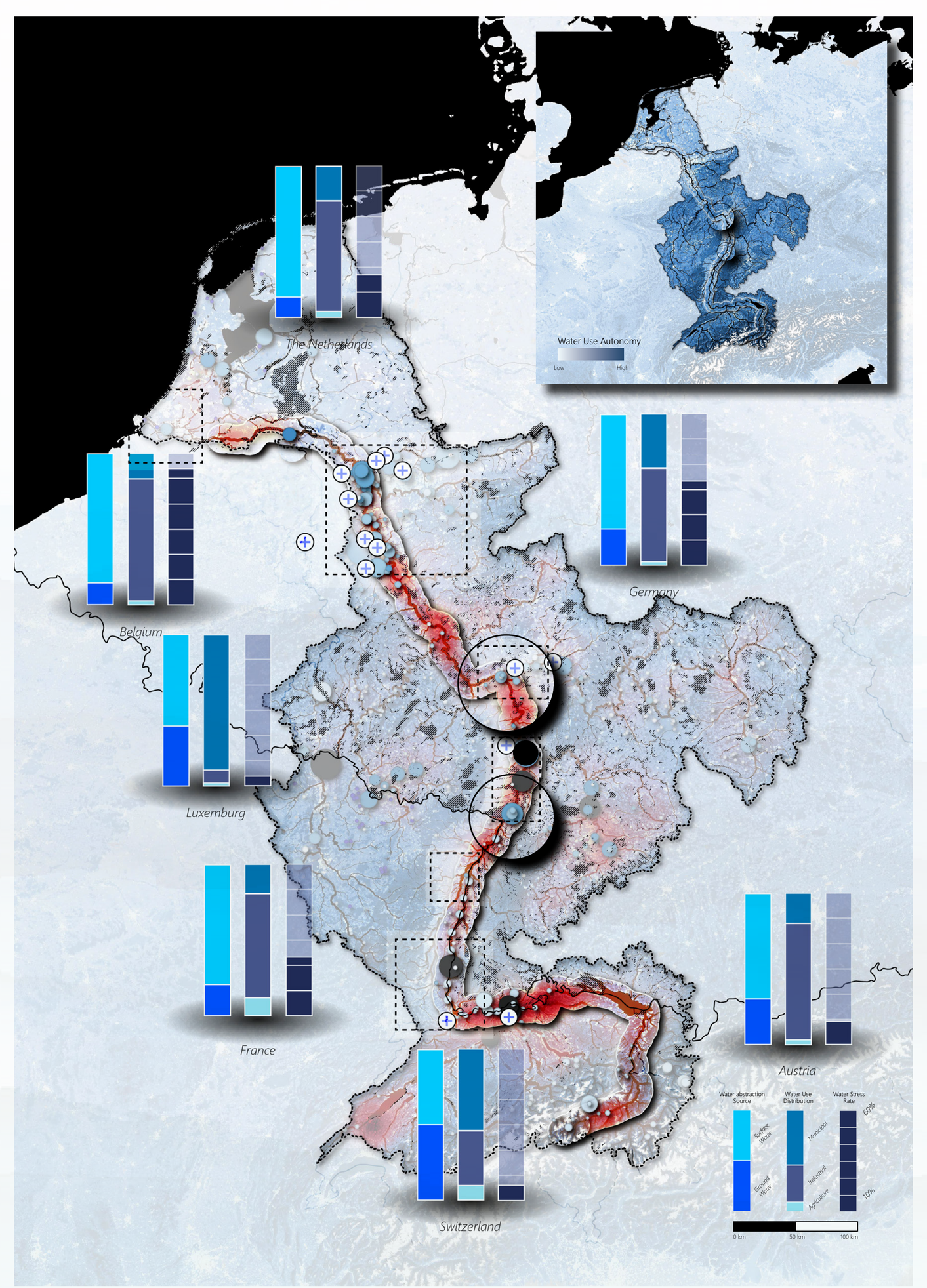

Figure: Autonomy of existing water use autonomy based on classified land use typologies.

Figure: Autonomy of existing water use distribution along the Rhine.

D. *Power Plant Water Use*

Power Plant Water Use — 1.5

"The lower the production capactiy and the higher the relation to dike management per power plants, the higher the potential for local autonomy"

Low production — High production

Scalar Interpretation: **Power Plants**

Translation of Data: Translation based on the production capacity of the power plants of the Rhine. Data is provided by Global Energy Observatory (2019). Additional Translation is made based on the relationship per classification of power plant to Water Use (W=1), Safety (W=3) & Dike relations (W=0.5)

The hydroelectric power plants in France (D3) and the energy facilities associated with German coal and gas industries (D1) rely significantly on this water source. The location of these power plants is vital in the context of local dike autonomy, especially concerning nuclear power plants. Due to the high safety risks associated with nuclear energy, the potential for local autonomy (D2, D4, D5) is reduced.

E. *Water Dependent Regions*

Water Dependent Regions — 2.0

Weight in (sub)calculation: 0% 25% 50% 75% 100%

Rule of Autonomy: "The higher the dependency of water per region, the larger the need arises for dikes to control a constant water flow, the higher the possibility for local autonomy"

High dependency — Low dependency

Scalar Interpretation: **Shapefile Areas**

Translation of Data: Translation of the spatial data provided by the IKSR (BAFG, 2015), highlighting the regions that are dependent on a constrant source of water. Often these locations are wetlands or natural retention zones.

Based on datasets from the IKSR (BAFG, 2015), water-dependent regions, often natural retention zones or Natura 2000 areas, require a constant water supply for survival. Dikes can redirect water flows to support these regions, enhancing natural infiltration and saturation rates while providing water buffers during periods of irregular water flow.

Water Use Distribution

Water Use Distribution — 1.25

Scalar Interpretation: **Point data**

Authoritative Regions

Authoritative Regions — 1.0

Scalar Interpretation: **Administrative Areas**

Localized Dike Autonomy

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