Adaptation Pathways for Flood Risk Management in Voerendaal East under Extreme Precipitation Scenarios through 2150

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Abstract

Climate change is expected to intensify extreme precipitation events, creating deep uncertainty for long-term flood risk management in Voerendaal East. This flood-prone area is located in the hilly landscape of South Limburg in the Netherlands. To address this uncertainty, this research develops adaptation pathways to manage extreme precipitation through the year 2150. Eight extreme precipitation scenarios are analyzed, combining four return periods (T25, T50, T100, T200) with medium and high climate projections.

The adaptation need of Voerendaal East is defined as the runoff volume that exceeds a water depth threshold of 0.25 m within a two-hour period at street level at the critical adaptation point. This point represents the location along the main runoff streamline where the maximum water depth occurs within the area of impact, which is the part of the catchment from which runoff converges toward the built-up area. Results show that the adaptation need reaches up to 70,000 m³ for T200H in 2150, while remaining negligible for T25M.

To meet the adaptation need, seven hydrologically effective measures are identified: buffer optimization, new buffer location, temporary barrier at home, temporary barrier highway, diversion, stream optimization, and infiltration. Diversion provides the highest effectiveness (80,000 m³), while temporary measures are the most cost-efficient. Infiltration and diversion are the most expensive, where the infiltration measure requires a large land surface of 400,000 m^2. Despite its large costs, the infiltration measure strengthens the landscape elements of South Limburg. The temporary measures and stream optimization require no land surface.

With these seven measures, 25 pathways are developed and evaluated from the perspectives of cost minimization, land minimization, avoidance of temporary measures, avoidance of temporary barriers at home, flexibility (choice and order of measures) and landscape integration. Buffer optimization emerges as the no-regret measure due to its favorable balance of cost, hydrological effectiveness and land requirement. Therefore, this measure serves as the first step in all pathways, except for the diversion pathway. It is assumed that responsibility for the initial measure of the pathways is not placed directly on citizens, but initially lies with the Limburg Water Authority.

The findings show that, overall, the flexible pathways outperform the rigid (diversion) pathway by reducing both overinvestment and land requirements. However, when the infiltration measure is applied, the rigid pathway becomes cheaper in terms of both cost and land use.

Keywords: extreme precipitation scenarios, adaptation need, climate adaptation measures, adaptation pathways, adaptation pathways perspectives

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1. Introduction

1.1 Background

Climate change affects the hydrological cycle and is expected to intensify extreme precipitation events as global temperatures rise (O'Gorman, 2015). An example of such an extreme precipitation event has been on the 13th and 14th of July in 2021 in the area of the Eifel, Ardennes and Limburg. This caused extreme discharges and runoff, leading to floodings in these areas. According to Van Kester and Maas (2023) the total amount of casualties was 228 people and the total damage was estimated on 40 billion euros. In Limburg, the Netherlands, there were no casualties and the total damage was estimated at 433 million euros (Asselman & Van Heeringen, 2023).
Voerendaal, a municipality in South Limburg, experienced heavy flooding during the extreme precipitation event of 2021. The combination of the extreme precipitation and the steep hillside caused large volumes of water to flow into the urban area of Voerendaal.
Waterschap Limburg, the municipality of Voerendaal and WSP explored measures for anticipating extreme precipitation events and potential flooding in Voerendaal. This is part of the Water in Balance program, that is focused on anticipating on flooding and drought in the province of Limburg (Waterschap Limburg, 2017).

1.2 Problem Statement

In order to anticipate on these floods in the long term, STOWA provides future extreme precipitation scenarios for the Netherlands (STOWA, 2024). However, modelling intensities of these extreme events remains deeply uncertain due to the long-term uncertainty of climate change itself (Zolghadr-Asli et al., 2022). This makes it challenging for water managers and policy makers to optimize water systems effectively. To deal with deep uncertainty of extreme precipitation in the long term, the Adaptation Pathways (AP) approach provides a flexible method (Haasnoot, Kwakkel, Walker, & ter Maat, 2013).

1.3 Research Aim and Research Questions

The aim of this research is to provide insight into the costs and spatial integration of different adaptation pathways under extreme precipitation scenarios, in order to manage long-term flood risks in Voerendaal East until 2150. The following research question is formulated:

What are possible adaptation pathways for Voerendaal East to manage future extreme precipitation through 2150, considering hydrological effectiveness, costs and spatial integration?

To answer this research question, the following sub-questions are formulated:

- *How do future extreme precipitation scenarios affect the adaptation need for Voerendaal East?*
- *What are hydrologically effective measures to manage extreme precipitation, and what are their costs and spatial integration?*

1.4 Scope

The climate adaptation measures in this research are evaluated on hydrological effectiveness, costs and spatial integration. These measures are applied within the boundaries of the project area, as outlined in Section 3: Case Study Area – Voerendaal East. While this research offers insight into potential adaptation pathways, it does not examine the practical implementation of these climate adaptation measures.

1.5 Readers Guide

This report starts with a theoretical framework. This is followed by a description of the case study area, Voerendaal East. Then, the methodology is presented and after that the results section is outlined. The discussion interprets and compares the results, addresses implications and limitations, and provides recommendations. Finally, the conclusion answers the research questions.

2. Theoretical Framework

Climate scenarios are a crucial part of adaptation pathways, this theory is discussed in subsection 2.1. This report adopts the Adaptation Pathways framework as its theoretical basis, this framework is elaborated in subsection 2.2. The spatial integration component of this report is elaborated based on theory related to the landscape concept and its relevance for climate adaptation, as discussed in subsection 2.3.

2.1 Climate Scenarios

In climate research, scenario planning is essential due to the high uncertainty in model projections (Riahi et al., 2017). The Intergovernmental Panel on Climate Change (IPCC) develops climate scenarios using Representative Concentration Pathways (RCPs), which represent different scenarios of greenhouse gas concentrations that determine radiative forcing (Riahi et al., 2017). These concentrations are influenced by socio-economic developments described by Shared Socioeconomic Pathways (SSPs). Combining RCPs and SSPs creates scenarios that integrate climate and socio-economic futures (Riahi et al., 2017).

These scenarios form the basis for extreme precipitation projections. Extreme precipitation statistics are derived through extreme value analysis of observed time series (Kourtis & Tsihrintzis, 2022). These statistics are summarized in intensity–duration–frequency (IDF) curves, which show how precipitation intensity depends on the return period and precipitation duration. Updating these curves with new climate data is crucial for the design, planning, and engineering of water management systems to minimize flood risk (Kourtis & Tsihrintzis, 2022).

According to Schoof and Robeson (2021), IDF curves can be updated by multiplying current extreme precipitation statistics by a change factor. These change factors are calculated as the ratio between simulated precipitation statistics for the future climate and those for the current climate. Such simulations are performed by downscaling global climate model outputs to regional climate models for different climate scenarios (Schoof & Robeson, 2021).

In the Netherlands, precipitation statistics from KNMI are translated by STOWA into extreme precipitation statistics for water management purposes (STOWA, 2024). STOWA has defined three greenhouse gas scenarios based on climate model results from KNMI, which are derived from the IPCC RCPs model outputs (STOWA, 2024). These scenarios represent low, medium, and high emission pathways. Extreme precipitation statistics are calculated with change factors for each climate scenario across different return periods, projection years, and precipitation durations.

For example, under the highest scenario for the projection year 2100, a storm with a 100-year return period (T100) is expected to produce 84 mm of precipitation within two hours (STOWA, 2024). A 100-year return period means there is a 1% probability of exceeding this precipitation intensity in any given year.

2.2 Adaptation Pathways

Scenario planning is widely applied in climate change adaptation research (Butler et al., 2020). In order to support decision-making in the face of deep uncertainty, Dynamic Adaptive Policy Pathways (DAPP) provide a method to determine how and when to respond to different climate scenarios (Haasnoot, Warren, & Kwakkel, 2019).

DAPP combines two methods: Dynamic Adaptive Planning (DAP) and Adaptation Pathways (Haasnoot et al., 2019). The central principle of DAP is that a policy must be flexible and adapt over time as new information becomes available. Triggers for initiating action, as well as the corresponding responsive actions, should be defined in advance (Walker, Marchau, & Kwakkel, 2019). In the AP approach predefined actions are implemented depending on how future conditions evolve (Werners et al., 2021). The key difference between the two approaches is that Dynamic Adaptive Planning (DAP) follows a single, flexible pathway that can be adjusted in response to triggers, whereas Adaptation Pathways (AP) offer multiple predefined routes, allowing decision-makers to switch paths depending on how future scenarios unfold (Haasnoot et al., 2013). This report uses only the theory of Adaptation Pathways.

Adaptation Tipping Point (ATP) is a key concept of the AP approach. ATP is the point where the current action does not meet the condition of success of the predefined system (Haasnoot et al., 2013). A new action follows or builds on the previous one, and a sequence of such actions forms a pathway. The most promising pathways can be illustrated with an adaptation pathways map, such as a metro map or a decision tree. The most promising pathways are based on costs, benefits and stakeholder values (Haasnoot et al., 2013).

2.3 Landscape Concept

According to Galan, van der Jagt, and Runhaar (2023), the potential of the landscape concept can be used to develop integrated visions, which serve as a precondition for addressing climate change adaptation. The landscape concept has an ecological, cultural, social, political, and economic dimension that interact with each other (Galan, van der Jagt, & Runhaar 2023).

An understanding of the interaction between human and their environment is therefore crucial in climate adaptation planning. According to Wu (2025) interactions between human activities and the landscape influence not only the physical form of the landscape but also its character (Wu, 2025). Rapid changes in the landscape can alter its character, potentially leading to a monotonous and homogeneous environment (Wu, 2025). Therefore, a landscape character assessment is essential to ensure its landscape compatibility with future spatial interventions (Wu, 2025).

3. Case Study Area – Voerendaal East

3.1 Introduction Case Study Area

Voerendaal is a village located at the foot of a hilly area, which lies to the south of Voerendaal. The village is bordered by the A79 highway to the south, the A76 highway to the east, and a railway line to the north. The elevation map and land use map of the area can be found in Figure 17 and Figure 18 of Annex B. The black line indicates the catchment area of Voerendaal East, which defines the project area for this report. The built-up area is shown in red.

Due to the elevation differences, water flows toward Voerendaal East and collects in the Cortembacherbeek, shown in Figure 1. The Cortembacherbeek passes through a culvert under the A79, where a viaduct is also located. From there, the stream flows through the built-up area of Voerendaal East.

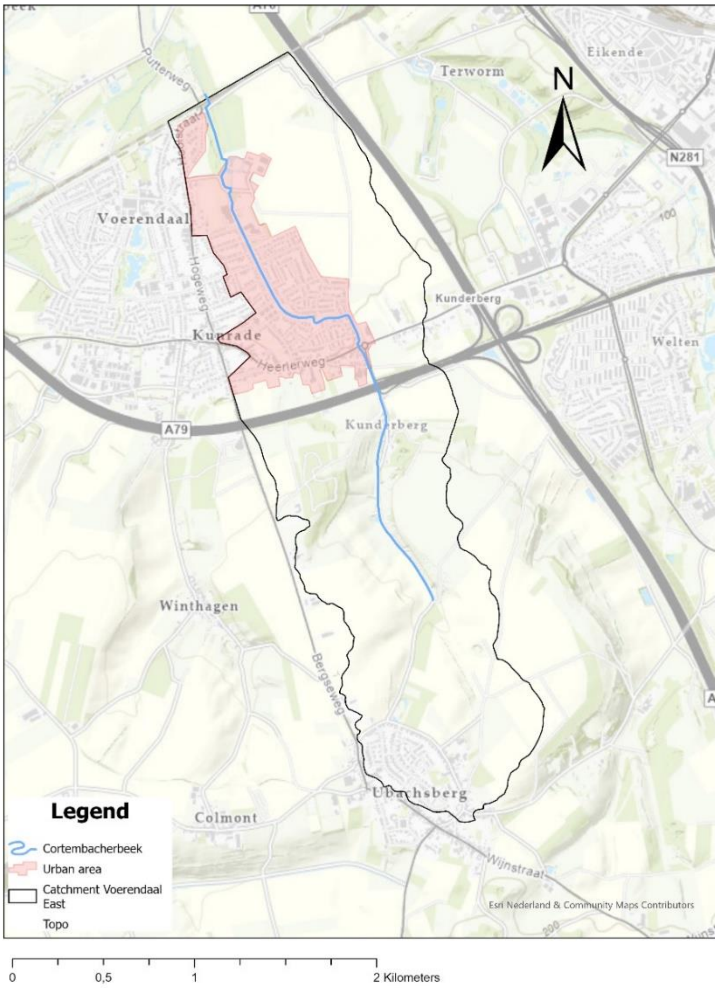

Figure 1 - Catchment area Voerendaal East

3.2 Protection Norms

The protection standards for Voerendaal and its surroundings are shown in Figure 2. It can be seen that the built-up area of Voerendaal has a protection standard of 1:25, while the built-up area of

Ubachsberg has a protection standard of 1:100. Ubachsberg is situated on the top of a hill, whereas Voerendaal lies at the foot of the hill. Waterschap Limburg has set a province-wide goal to explore additional measures that could achieve a T100 protection level.

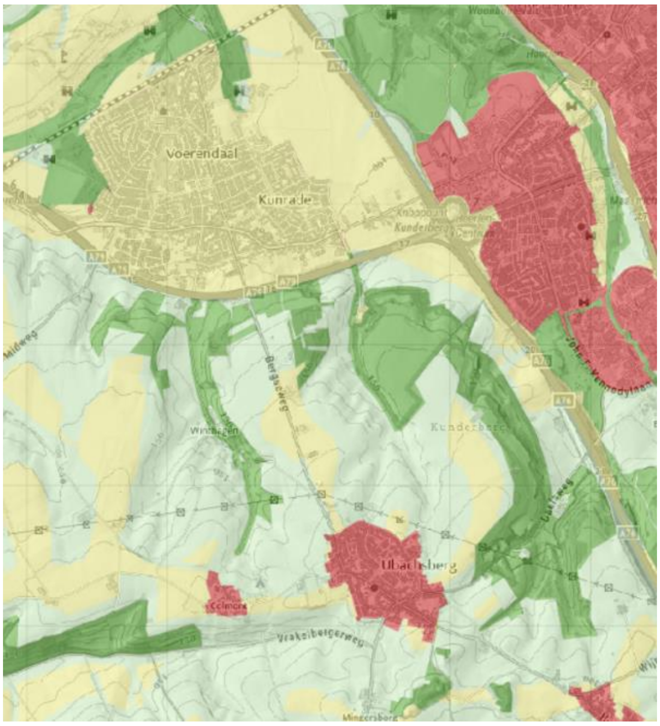

Figure 2 - Protection norms Voerendaal (Provincie Limburg, n.d). Light green - 1:10, yellow - 1:25, red - 1:100, dark green - no protection standard.

3.3 Landscape Elements South Limburg

The protected area of the National Landscape South Limburg consists of three landscape types: plateau, slope, and valley. The core qualities of the landscape types are characterized by landscape elements. The four core qualities and the landscape element are described in the Environmental Regulation of the Province of Limburg (Province of Limburg, 2025).

Relief

Relief is a core quality characterized by steep slopes, steep edges, stream valleys, dry valleys, sunken lanes, small erosion gullies and terraced slopes (Province of Limburg, 2025).

Open and enclosed spaces

This core quality is characterized by the open spaces of terraces, while the enclosed spaces are created in the small villages, valleys, and steep slopes. This creates a contrast between open and enclosed spaces (Province of Limburg, 2025).

The green character

The green character is characterized by spring forests, stream valleys with green cover, slope forests, terraced slopes (graften), erosion gullies (grubben), and sunken lanes. The graften, grubben and sunken lanes have green cover, so therefore it strengthens the green character (Province of Limburg, 2025).

Cultural-historical heritage

Expected and known archaeological values, including mottes, castles, historic architecture, historical-geographical elements, spatial patterns (such as road and parcel structures), fortifications, underground limestone quarries, and hedgerows (Province of Limburg, 2025).

When the impact of climate adaptation measures is weakening the core qualities, other measures are needed to compensate (Handvat Nationaal Landschap, n.d.).

4. Methodology

The methodology is based on the Adaptation Pathways framework. The methodology is organized into the following subsections: Definition of Water Nuisance, Extreme Precipitation Scenarios, GIS-based Runoff Model, Co-Creation and Brainstorms, and Design Guidelines Adaptation Pathways.
Identifying the ATPs requires first defining the success condition for Voerendaal East. The approach for defining this condition is discussed in the first subsection, Definition of Water Nuisance.
Next, the extreme precipitation scenarios are introduced. These scenarios serve as input for calculating the adaptation need for each scenario. The method for calculating this adaptation need is explained in the subsection GIS-based Runoff Model.
To determine the timing of the ATPs, the hydrological effectiveness of the adaptation measures is assessed. The approach for developing the adaptation measure portfolio is presented in Co-Creation and Brainstorms. This subsection also explains the method for estimating costs and integrating the measures spatially.
Finally, the method for mapping the adaptation measures and their ATPs is described in Design Guidelines Adaptation Pathways.

4.1 Definition of Water Nuisance

The definition of water nuisance forms the starting point of this research. It is defined as the critical water depth at which damage to the built environment occurs. In the model outputs of the Preferred Variant (VKV) report of Voerendaal, the critical water level is defined as 0.15 m of water depth against a building (WSP, 2025). Assuming an average pavement height of 0.10 m (Moftakhari et al., 2018), the total critical water depth is approximately 0.25 m at street level. The definition of water nuisance in this research is as follows:

For Voerendaal East, water nuisance is defined as exceeding a water-depth threshold of 0.25 m at street level.

In this research, the water depth is calculated using Manning's formula (Venutelli, 2005), under the assumption that the street is conceptualized as a canal with a rectangular cross-section:

$$Q = \frac{1}{n} \cdot A \cdot R^{\frac{2}{3}} \cdot S^{\frac{1}{2}}$$

Where:

Q: Discharge (m^3/s)
n: Manning roughness coefficient ($s/m^{1/3}$)
A: Wetted area (m^2)
R: Hydraulic radius (m)
S: Slope (-)

For a rectangular cross-section the wetted area and the hydraulic radius are respectively defined as:

$$A = b \cdot h$$

$$R = \frac{A}{(b + 2 \cdot h)}$$

Where:

b: Width (m)
h: Water depth (m)

The Manning roughness coefficient (n) is assumed to be 0.012 for street surfaces (WSP, 2025). The discharge (Q) is calculated using the GIS-based runoff model, which is presented in Subsection 4.3. The slope (S) is determined by dividing the elevation difference of a street section by its length, while the critical width (b) is measured in the basemap of GIS. By substituting the formulas, the water depth can be solved numerically using the bisection method. Conversely, when the water depth is known, such as the threshold of 0.25 m, the corresponding discharge can be determined. In this research, the discharge is assumed to be constant over time. Under this assumption, the total volume can be calculated over a fixed duration of the precipitation. The total volume that exceeds the threshold of 0.25 m is defined as the adaptation need.

4.2 Extreme Precipitation Scenarios

The input of the runoff model is extreme precipitation scenarios based on data from STOWA (2024). The climate scenarios used in this research are the medium and high scenarios. Projection years 2050, 2100, and 2150 are applied, consistent with STOWA (2024). The intensities of extreme precipitation under the current climate are defined by the basic statistics (STOWA, 2024), which vary depending on the return period and the precipitation duration.
The return periods T25, T50, T100, and T200 are selected for this research. T25 is included because it represents the protection standard for the urban area of Voerendaal, and T100 is chosen as it reflects the protection ambition. The basic statistics provided by STOWA (2024) do not account for regional factors such as elevation differences. To incorporate the orographic effect of the hilly landscape, both the return period of the protection standard and the ambition are multiplied by a factor of two (Asselman & Van Heeringen, 2023). Therefore, the return periods T50 and T200 are also examined as scenarios in this research.
The basic statistics for all scenarios are shown in Figure 3 for the year 2025. A fixed precipitation duration of two hours is used, in line with the VKV report (WSP, 2025). For future projection years, the precipitation intensity is calculated by multiplying the basic statistics by the change factors of STOWA (2024). This factor depends on both the projection year and the selected climate scenario, as shown in Table 1 below.

Table 1 - Changing factors for medium and high climate scenarios (STOWA, 2024)

	2025	2050	2100	2150
Medium climate	1.000	1.045	1.098	1.110

scenario				
High climate scenario	1.000	1.072	1.234	1.331

The change factors are linearly interpolated between the given projection years, with a time step of five years. These interpolated factors are then multiplied by the basic statistics to obtain the precipitation intensities for each scenario.

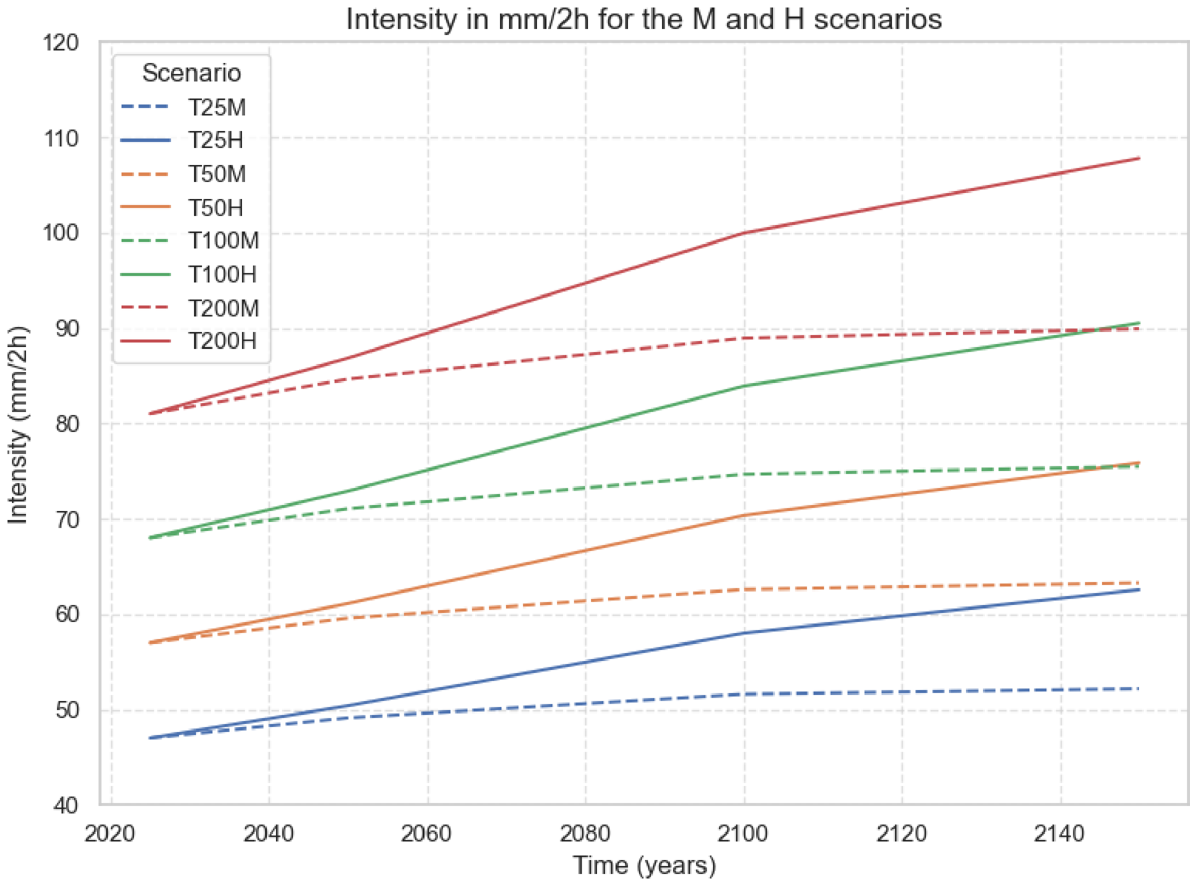

Figure 3 - Intensities precipitation per scenario

4.3 GIS-based Runoff Model

Both the volume and spatial distribution of runoff are integrated into streamlines. Streamlines are used in this research to determine which buildings are vulnerable to flooding and to determine the adaptation need. Streamlines are identified using a GIS-based runoff model that applies the flow accumulation function, as illustrated in the Data Action Model (Figure 14, Annex A). The input datasets for the runoff model include LGN land use, AHN elevation, runoff coefficients, and the precipitation intensity. The runoff is calculated by multiplying the flow accumulation value by the precipitation intensity.

Land use data is sourced from the Landelijk Grondgebruiksbestand Nederland 2022 (LGN, 2022). This is a raster dataset with a 5 m resolution containing 51 classes such as forest, water, agriculture, infrastructure, and urban areas. For the runoff model, the resolution is set to 0.5 m, which matches

with the Algemeen Hoogtebestand Nederland 5 Digital Terrain Model (Rijkswaterstaat, 2023) elevation dataset. Both datasets are clipped to reduce data volume.
In some locations, AHN elevation data requires adjustments to ensure proper functioning of the flow accumulation tool, particularly near culverts or under infrastructure such as the A79 highway. This is addressed using vector data representing connection surfaces. The minimum elevation within each surface is extracted using the zonal statistics function, producing a raster where each surface has a constant minimum elevation. This raster is merged with the clipped AHN dataset, and the fill function is applied to remove sinks that would otherwise trap water and disrupt flow calculations.
The output of the fill function is then used as input for the flow direction tool. This tool determines the flow paths of stream lines by comparing the elevation of each cell with its eight surrounding neighbors and selecting the direction with the steepest downslope.
The resulting flow direction raster serves as input for the flow accumulation function. The other input for this function is the runoff, which is estimated using local runoff coefficients provided by Waterschap Limburg. The runoff coefficients applied by Waterschap Limburg are based on slope and land use, as shown in Table 2. To account for these coefficients, a merged raster dataset combining slope and land use data is created. The slope is calculated using the slope function with the AHN elevation dataset as input. The slope raster is classified into four categories, and the land use raster into five categories, resulting in a combined dataset with 20 classes representing slope and land use combinations. These classes correspond to the runoff coefficients provided by Waterschap Limburg. One assumption is that the land-use category 'water' is assigned a runoff coefficient of 1. Although these coefficients are based on an intensity of 63 mm in two hours, they are applied to all intensities in this research.

Table 2 - Runoff coefficients for an intensity of 63 mm in two hours (Waterschap Limburg, n.d.)

	< 4%	4 – 7%	7 – 12 %	>12 %
Arable land	0.38	0.49	0.52	0.78
Grassland/orchard	0.31	0.33	0.37	0.48
Forest	0.31	0.33	0.35	0.43
Paved surfaces and water	1	1	1	1

In summary, the flow accumulation tool estimates runoff at any point along a streamline by multiplying the flow accumulation value by the precipitation intensity, providing spatially distributed runoff across the catchment. The flow accumulation function sums all cells upstream that contribute flow to the point of interest. To calculate runoff correctly in m^3, the precipitation intensity must be multiplied by the cell area, which is 0.25 m^2 (based on a 0.5 m resolution). A key assumption is that runoff remains constant over time, as the flow accumulation function computes one value and not a timeseries. The streamlines are illustrated in Figure 16 in Annex B.
The outcomes of the flow accumulation model are verified against the outcomes of the water system analysis for the Voerendaal area, this verification is illustrated in Annex C. The verification points are selected upstream in the catchment area, specifically in locations where sewer systems and buffers do not influence runoff. This is important because the flow accumulation model does not account for the effect of sewers or buffers.
The same runoff coefficients, elevation and land use datasets as in the verification model are used. For a T25 event, the GIS-based runoff model produces on average 98% of the runoff of the verification model. For a T100 event, this decreases to 77%. The position of the streamlines corresponds well to

the verification model except at one location where the flow splits into two branches. The route of the split streamline of the verification model is shown in red in Figure 16 in Annex B. The GIS-based runoff model applies an all-or-nothing principle, which directs all water into the built-up area. In this report, streamlines from the GIS-based runoff model are used.

4.4 The Critical Adaptation Point

Downstream, runoff increases as flow accumulation increases. Additionally, variations in street cross-sectional width and longitudinal slope influence the resulting water depth. Consequently, the adaptation need differs at each point along the streamline.
In this research, only the streamline with the highest potential to cause damage to residential properties is analyzed. The area of impact is defined as the area with the greatest potential for damage within the project area, as shown in Figure 4. Within this area, a point is selected where the adaptation need is most critical: the critical adaptation point. This point represents the location with the highest potential water depth. Meeting the adaptation need at this point ensures that the adaptation need is satisfied throughout the entire area.

Figure 4 - Area of impact

The critical adaptation point is determined by selecting the highest precipitation intensity, which results in the greatest flow accumulation. This discharge (flow accumulation converted to m^3/s, assuming constant runoff) is then applied in Manning's formula after adjusting for the current buffer capacity. The current buffers and their capacity are illustrated in Figure 6, in the results section. Eight points are selected for water depth calculation, chosen where the street section has the smallest cross-sectional width. The final input and output for Manning's formula are presented in Table 5 in Annex D. This shows that cross-section four is the critical adaptation point, with a critical water level of 0.46 m.

The water levels are not verified against the model because, in that model, runoff splits before reaching the area of impact, resulting in different runoff results for this area. Furthermore, the influence of the sewer system within the built-up area is greater than upstream, making water level verification invalid. Therefore, this research continues using the water levels and runoff derived from the GIS-based runoff model and Manning's formula.

The adaptation need is calculated for each scenario at the critical adaptation point. The adaptation need equals the computed runoff minus the existing buffer capacity and the discharge corresponding to a water depth of 0.25 m.

4.5 Co-Creation and Brainstorms

A first set of measures is developed through a co-creation with water experts from WSP. The starting point for this session is the calculated adaptation need for the worst-case scenario (T200H). The task was to propose hydrologically effective measures without considering costs or spatial constraints. Working in pairs, participants designed and mapped two sets of measures on an overview map of the catchment area, which can be found in Annex E.

After a pre-screening on hydrological effectiveness, the resulting list of measures formed the starting point for three brainstorm sessions. The measure *temporary barrier at home* was added after the co-creation. The list of measures after pre-screening is as follows:

- Optimization current buffers
- New buffer location
- Temporary barrier Highway (A79)
- Optimization stream (Cortembacherbeek)
- Diversion
- Infiltration
- Temporary barrier at home
- Dams upstream

Three brainstorming sessions are held to define the method for each component: hydrological effectiveness, cost and spatial integration. Water experts from WSP participated in the sessions on hydrological effectiveness and cost, while WSP's environmental managers contributed to the session on spatial integration. The method for the hydrological effectiveness and the costs of the measures is discussed in the results section. This method specifies when effectiveness and costs are based on designs and calculations by WSP.

The spatial integration brainstorm concluded that the most important factors for spatial integration are landscape integration, societal and political support, and the legal environmental framework. In this

research, the legal framework was excluded from consideration. An example of the legal environmental framework is the Natura-2000 area. Support and the landscape integration are assessed quantitatively.
For the quantitative assessment, the additional land area required for a measure is used as a parameter for both landscape integration as for support. The larger the area needed for a measure, the greater the potential impact on landscape integration and support. In general, measures requiring more space tend to have lower levels of support, because more land acquisition is needed. However, other factors also influence support, such as cost, effectiveness, landscape integration, and stakeholders' willingness to provide land through sale or exchange. For the landscape integration the impact depends on the existing landscape elements and the specific impact of each measure on these elements, as described in the Case Study Area. The impact of the required area for a measure could be weakening, neutral or strengthening. The size of the required land area therefore determines the magnitude of this effect.
During the brainstorming session, it was noted that dams upstream have a strong weakening effect on landscape integration. Consequently, the measure of applying a dam with a minimum height of 3 m in the valley has been excluded from further analysis.

4.6 Design Guidelines Adaptation Pathways

The adaptation need for each scenario and the hydrological effectiveness of adaptation measures are the inputs for constructing the pathways and determining the timing of tipping points. Adaptation pathways consist of measures that follow one another to meet the adaptation need.
To reduce the number of pathways, pathways can start with the same measure, known as a no-regret measure (Haasnoot et al., 2013). The measure with the most favorable characteristics in terms of hydrological effectiveness, cost, and spatial integration will be selected as the no-regret measure. It is assumed that the Water Board of Limburg does not consider temporary measures desirable. Therefore, measures such as temporary barrier at home and temporary barrier highway are excluded as no-regret measure.
In addition, each measure can only be implemented once, and it is assumed that measures require a period of five years to be completed.
To indicate when and which measures are needed, the scenarios are shown under the adaptation need (below the x-axis). The following time horizons are displayed: 2030, 2050, 2100, and 2150. The year 2030 was chosen as the starting point because measures require five years to be finished. From this, it can be determined when and which measures are necessary for a given time horizon.

5. Results

This section presents the results for the adaptation need per scenario, the portfolio of adaptation measures, and the adaptation pathways for managing flood risk in Voerendaal East.

5.1 Adaptation Need

The adaptation need for Voerendaal East is determined for the point where the adaptation need is at a maximum, the critical adaptation point. The adaptation need is assessed for eight extreme precipitation scenarios up to the year 2150 and is expressed as the volume (m³) that exceeds the critical adaptation point within a two-hour period. This volume is plotted over time in Figure 5, starting from the year 2025.

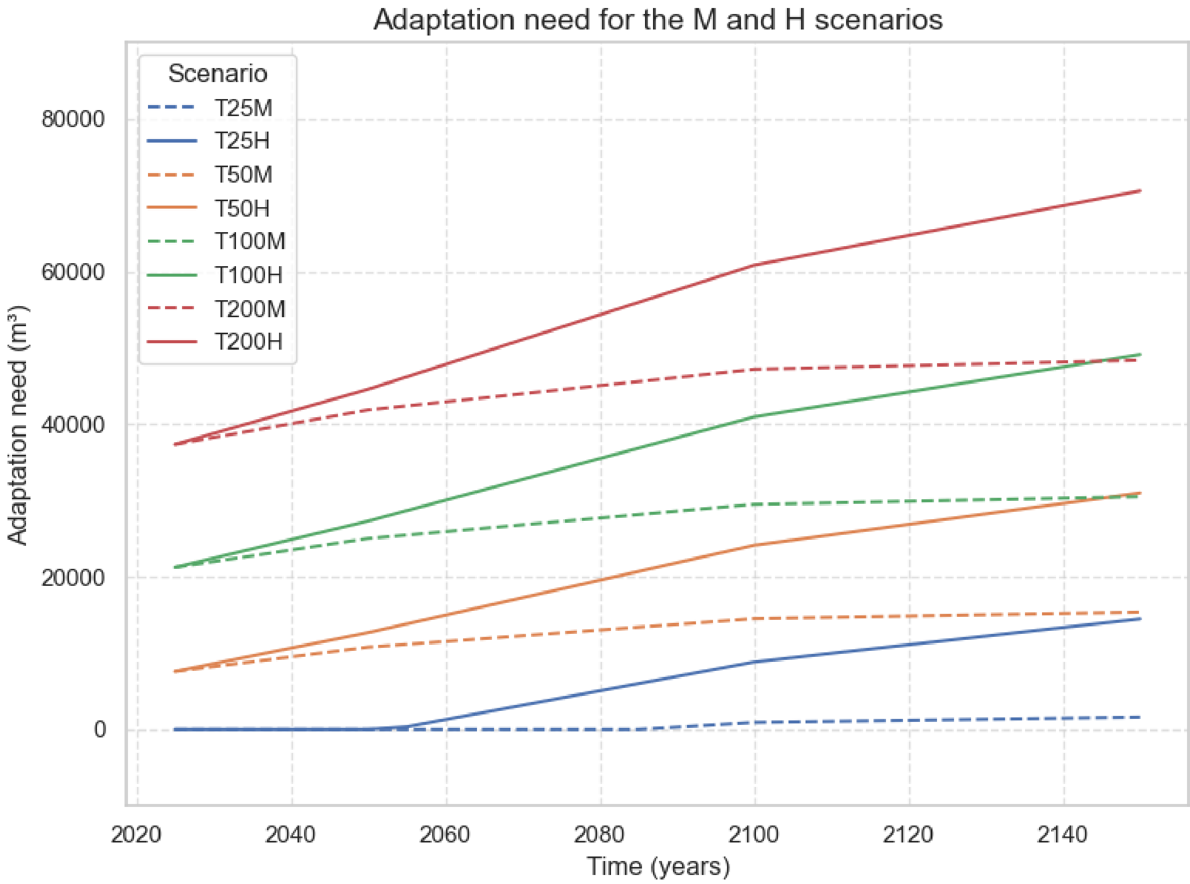

Figure 5 - Adaptation need per scenario

In general, the adaptation need under high climate scenarios increases more over time compared to medium climate scenarios. The graphs shows the same trend as the extreme precipitation graph shown in Figure 3.

By 2150, the adaptation need under a high climate scenario is comparable to that of a medium climate scenario with a return period twice as long. For instance, the adaptation need for scenario T100H in 2150 is similar to that of scenario T200M.

For scenario T25M, the adaptation need becomes positive from 2090 onwards, indicating that no measures are required before this year. After 2090, the adaptation need remains limited until 2150.

For scenarios T25H and T50M, a measure of 20,000 m³ is sufficient to meet the adaptation need through 2150, with no adaptation need for T25H until 2050.
In contrast to T25H and T25M, the T50 scenarios show an immediate adaptation need from the start year, beginning at approximately 10,000 m³. For the T100 scenarios, the initial adaptation need is 20,000 m³, while for the T200 scenarios it starts at 40,000 m³. The maximum adaptation need occurs under scenario T200H in 2150, reaching a volume of 70,000 m³.

5.2 Adaptation Measure Portfolio

To address the adaptation need, adaptation measures are required. This subsection presents a description of each measure and its location. It also provides an analysis of the hydrological effectiveness, associated costs, and additional land requirements for each measure. Where relevant to location or design decisions, considerations regarding landscape integration are included. The subsection concludes with a summary of the entire portfolio of measures.

5.2.1 Optimization Current Buffers

In this measure, existing buffers are either deepened, expanded with an additional compartment, or both. The hydrological effectiveness and the additional required area are based on the optimized buffer designs presented in WSP's VKV report. WSP also provided an estimate of the optimization costs, which are adopted for this measure. In addition to the buffer optimization costs, land acquisition is included in the total cost calculation.
The buffer locations are shown in Figure 6. Buffer 1 is deepened, resulting in an additional storage capacity of 3000 m³. Buffer 2 is both deepened and expanded on the southern side with an extra compartment, increasing its capacity by 8000 m³ and adding 4000 m² of surface area. Buffer 3 is deepened, providing an additional 2000 m³ of capacity. Buffer 4 is a newly constructed buffer compartment, contributing 3000 m² of area and 4000 m³ of extra buffer capacity. The capacity of Buffer 5 remains unchanged. A summary of the buffer characteristics and associated costs is provided in Table 3. With an additional area of 7000 m², the total cost of this measure is approximately X.

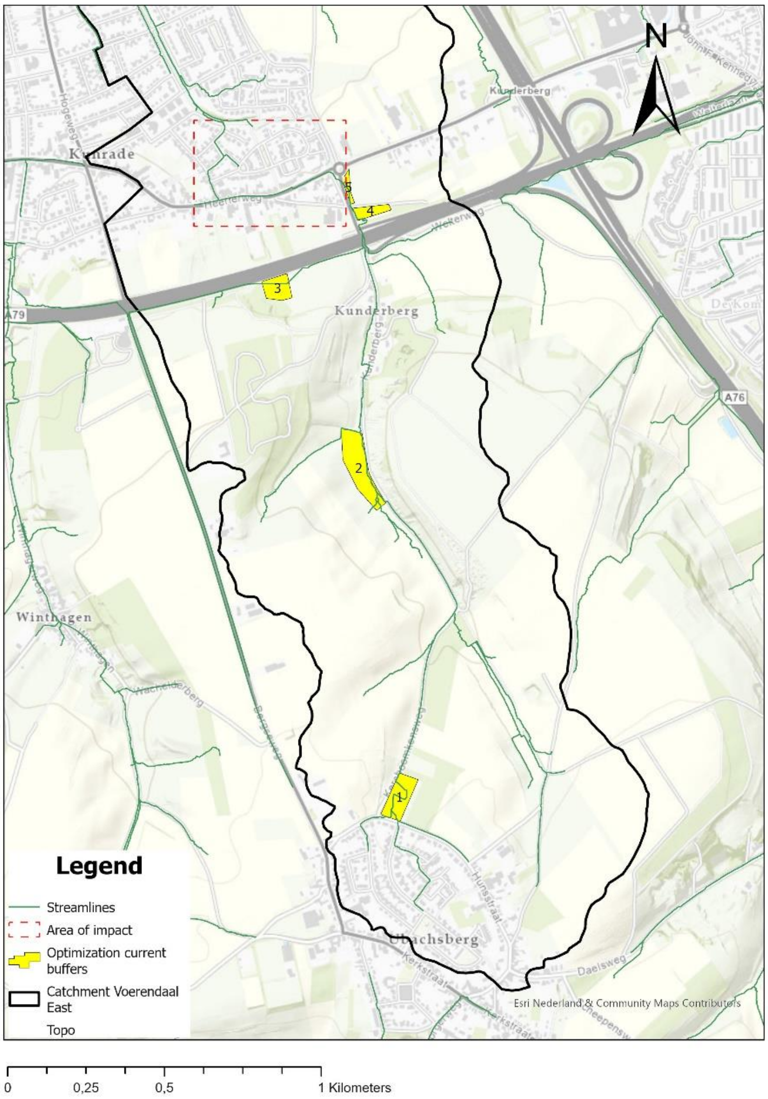

Figure 6 - Optimization buffers

Table 3 - Characteristics buffers

Buffer	Current capacity (m^3)	Extra capacity (m^3)	Costs (€)	Additional land (m^2)	Costs land (€)
1	5000	3000	X	0	X
2	10,000	8000	X	4000	X
3	5000	2000	X	0	X
4	0	4000	X	3000	X
5	1000	0	X	0	X
Total	20,000	20,000	X	7000	X

5.2.2 New Buffer Location

When selecting a new buffer location, the core landscape qualities of South Limburg and the hydrological effectiveness are taken into account. The first criterion is that there must be no overlap with cultural heritage. Secondly, forested areas are avoided to preserve the green character of the landscape. Additionally, the location is sought within valleys. This minimizes impact on the relief and maintains the semi-open, semi-enclosed character of these valleys. Streamlines also run through these valleys, making buffer placement hydrologically effective. From a hydrological perspective, arable land is the most suitable for conversion into buffers, as it generates the highest runoff among unpaved surfaces. Following these principles, a suitable area has been identified with an approximate surface of 15,000 m².

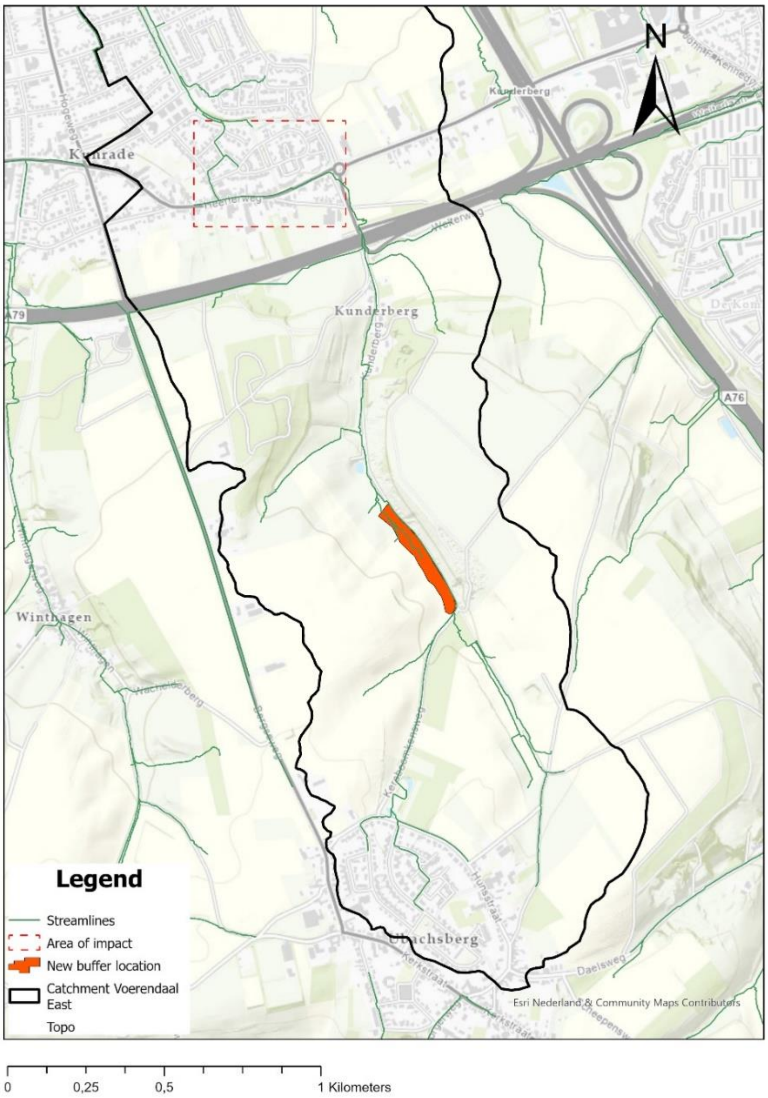

Figure 7 - New buffer location

The costs and effectiveness for this measure are based on WSP's buffer design and cost estimates. To calculate the effectiveness and costs of the new buffer, a comparison is made with the design of buffer 4 from the previous measure. For an additional capacity of 4000 m³, 3000 m² of land is required, with an estimated cost of X. Using this ratio, the effectiveness for 15,000 m² is projected at 20,000 m³ and the total cost is rounded to X (including land costs).

5.2.3 Temporary Barrier Highway

In this measure, water is retained by closing the road at the Kunderberg junction beneath the A79 viaduct using a temporary barrier. In case of flood risk, the underpass is closed. The elevation difference between the highway and the road below the viaduct is more than five meters. A barrier height of 4.25 m is assumed to prevent water from overtopping the highway. Using the AHN elevation data, the storage volume is estimated at approximately 10,000 m³. The effect of water backing up is not included in determining the effectiveness of this measure. The cost for this measure is estimated by WSP experts at X. No additional land area is required for this measure.

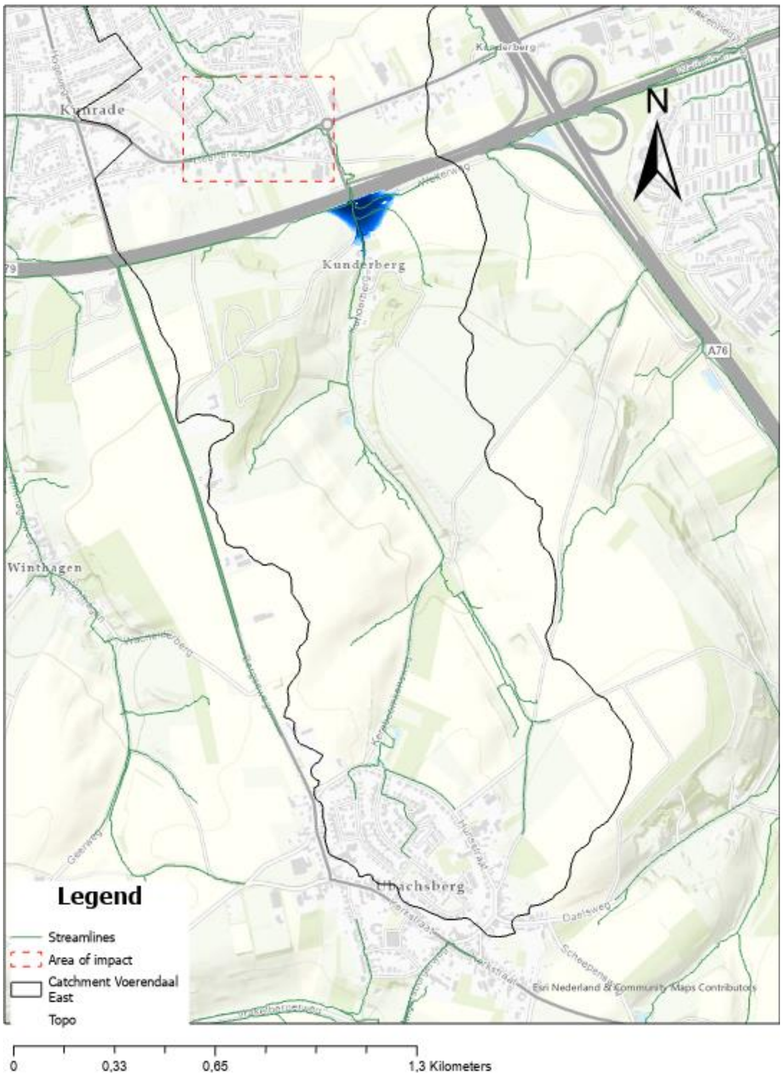

Figure 8 - Temporary barrier highway

5.2.4 Infiltration

In this measure, arable land with a slope greater than four percent will be converted into forest. The total area involved in this measure is 400,000 m², and the orange area in Figure 9 illustrates this area. In the GIS-based runoff model, the runoff coefficient for arable land with a slope above four percent is replaced by the runoff coefficient corresponding to forest within the same slope category, as shown in

Table 2. The change in this runoff coefficient results in a decrease in runoff of approximately 10,000 m^3.

Besides the hydrological effect, this measure has a strong strengthening impact on the green character of the area. Since the measure is implemented on sloped arable land, it will results in the creation of a slope forest. It also strengthens the open and enclosed spatial qualities of the landscape. The plateau has an open character, while the dry valley has a semi-open to semi-enclosed character. The slope forest will have a closed character, which strengthens the contrast between open and enclosed spaces. The required area for this measure is determined using GIS. To calculate the cost, this area is multiplied by the land price of X per square meter. Additionally, an estimated cost of X per hectare is included for forest establishment (Teeuwen, Reichgelt, & Oldenburger, 2020). In total, this measure costs X.

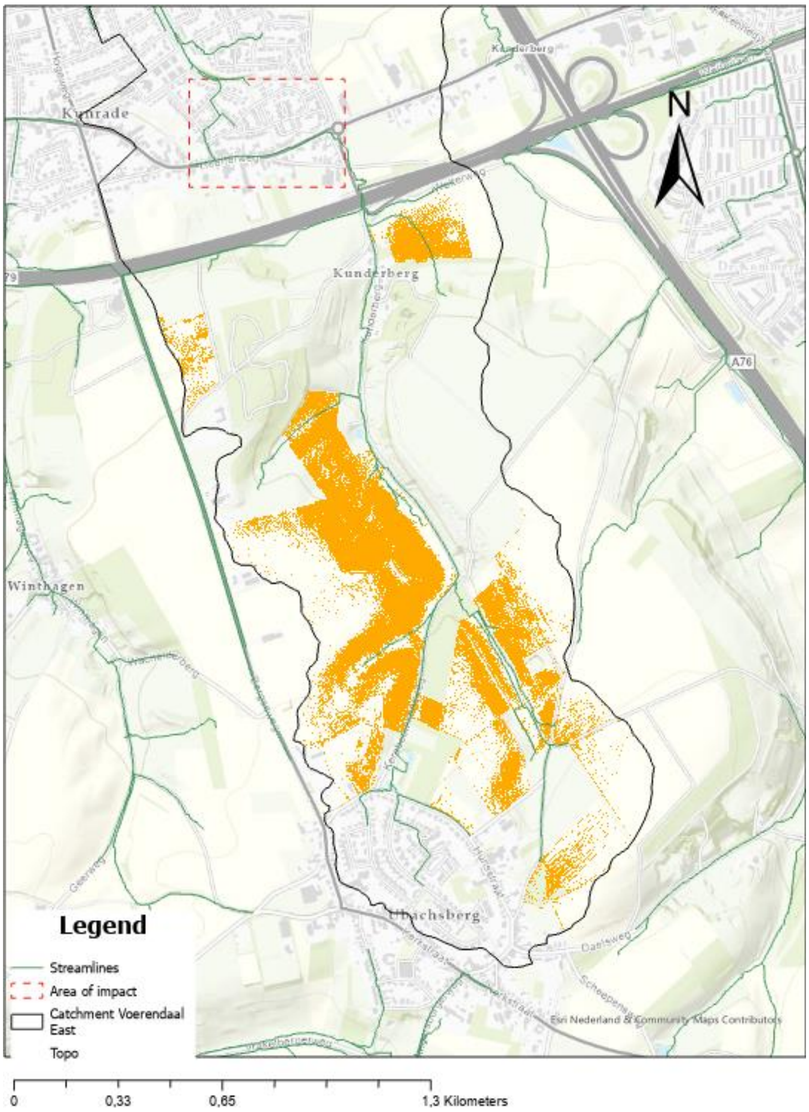

Figure 9 - Infiltration

5.2.5 Diversion

The location and design of the diversion are based on WSP's VKV report, with the diversion's position illustrated in Figure 10. It can be observed that the diversion will run through a newly planned residential area.

Modeling from WSP indicates that 50,000 m³ of water can be diverted, with a peak discharge of 9 m³/s through the culvert. This culvert connects Buffer 5 (see Figure 6) to the start of the diversion and passes beneath the roundabout. The culvert has a rectangular profile with a height of 1.5 m and a width of 4 m, allowing for a maximum peak discharge of 15 m³/s. Based on this capacity, it is assumed that up to 80,000 m³ of water can be diverted when operating at the full peak discharge of 15 m³/s. The diversion channel itself has a trapezoidal cross-section with a bottom width of 4 m, side slopes of 1:3, and a depth of 1 m. A Manning's roughness coefficient of 0.03 is applied in the calculations (WSP, 2025).
The cost estimates are based on WSP's calculations for this diversion, amounting to approximately X. The dimensions of the measure determine the required area, which is then multiplied by the land price. The required area is estimated at around 30,000 m². These land acquisition costs are added to the implementation costs of the diversion, bringing the total cost of this measure to approximately X.

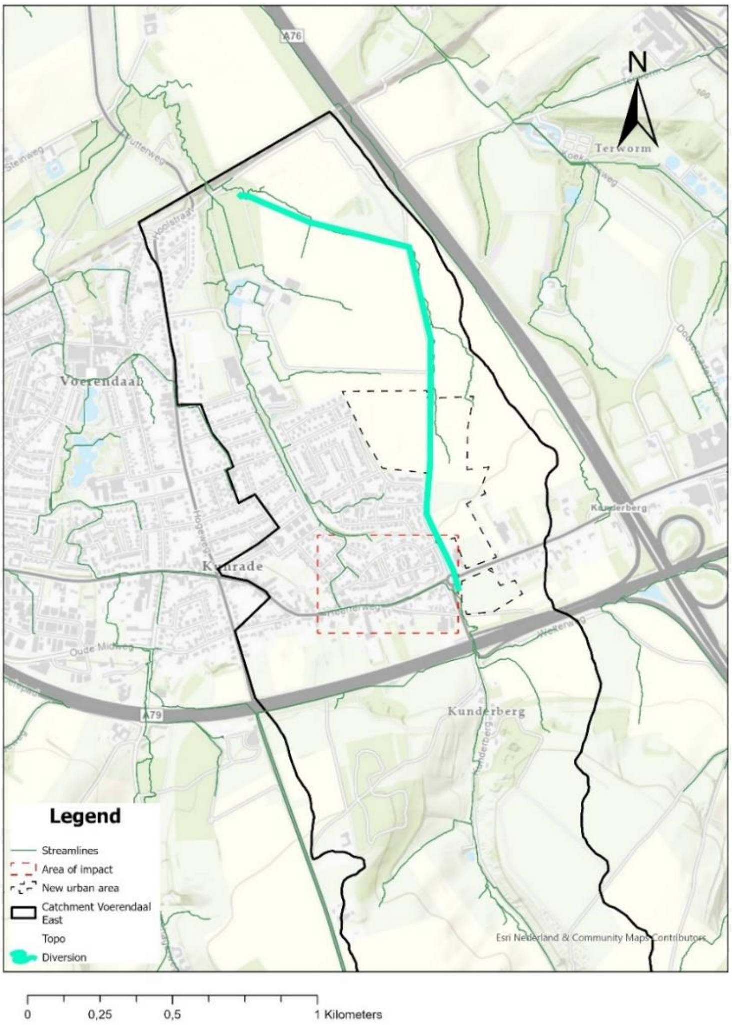

Figure 10 - Diversion

5.2.6 Optimization Stream

For this measure, the existing Cortembacherbeek stream and its culverts are reprofiled to increase flow capacity. The part of the Cortembacherbeek that is reprofiled is illustrated in Figure 11. The stream runs through a residential area in Voerendaal East, alongside a green strip. One bank will

remain vegetated and unmown to preserve the area's green character. Due to this vegetation, flow resistance increases. Therefore, a Manning's coefficient of 0.06 is assumed (Rizalihadi, 2019).
The stream will have a trapezoidal profile with a bottom width of 1 m, side slopes of 1:3, and a depth of 1 m. The slope used in the calculations corresponds to the average slope of the existing culverts of the Cortembacherbeek, and this value is applied to both the culverts and the stream. The discharge capacity of the reprofiled stream and its culverts is approximately 4 m³/s each, calculated using Manning's formula.
For the culvert, a rectangular profile of 2 m wide and 1.5 m high is assumed, with a water depth of 1 m to allow free flow. A Manning's coefficient of 0.03 is applied for the culvert.
With a peak discharge of 9 m³/s, the diversion measure can redirect about 50,000 m³ of water. In comparison, the reprofiled stream, with a capacity of 4 m³/s, can divert approximately 20,000 m³. Therefore, the hydrological effectiveness of this measure is estimated at 20,000 m³.
The cost of this measure is based on WSP's calculations for constructing a new culvert and constructing the diversion channel. Costs are expressed per linear meter for both the channel and the culvert, and then multiplied by the required lengths for this measure. No land acquisition is needed, so no additional costs are included for land. The total cost for this measure is estimated at X.

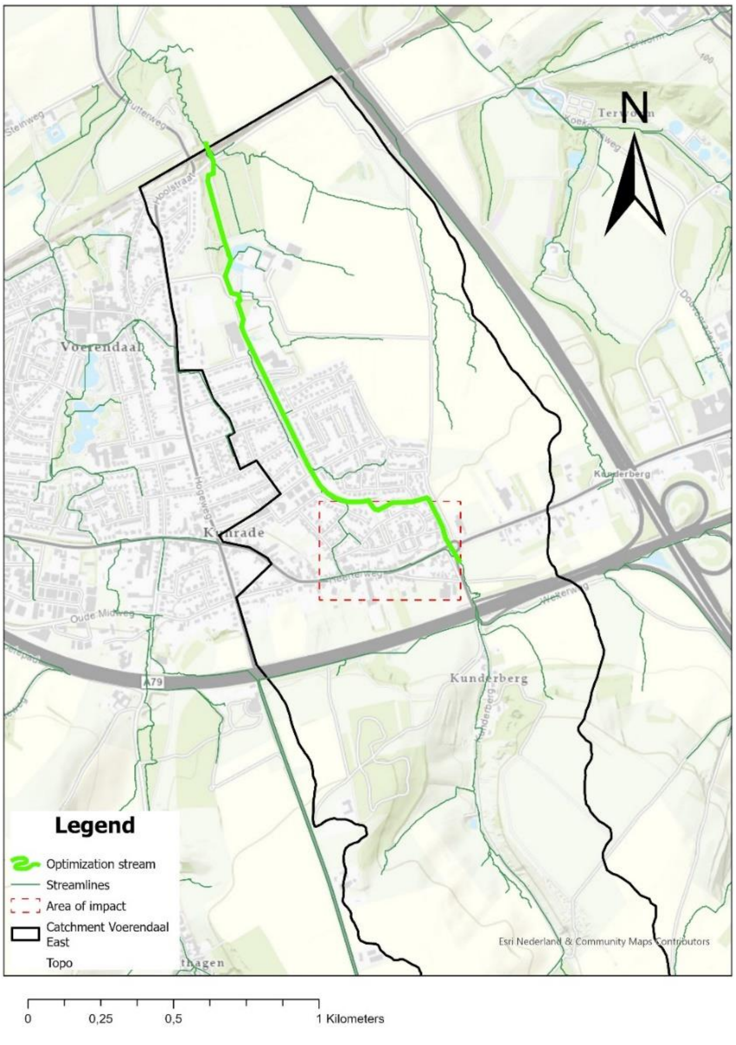

Figure 11 - Optimization stream

5.2.7 Temporary Barrier at Home

For this measure, a temporary flood barrier will be placed in the openings of each house during flood risk. This measure must be implemented privately by homeowners themselves, meaning that part of the responsibility for correct execution lies with the homeowner. The measure should be combined with an early-warning system from the water authority to inform homeowners when to install the barriers.

The number of openings to be protected depends on each individual house. Each barrier has a height of 600 mm and an adjustable width ranging from 780 mm to 1,100 mm. For wider openings, multiple barriers can be connected. The cost per barrier is €669 (Dam Easy®, n.d.), and it is assumed that each house requires an average of two barriers. Based on GIS estimates, approximately 100 houses are located along the flow path within the impact area. Therefore, the total cost for this measure is estimated at €200,000.

Since this measure can block water up to a height of 600 mm, it can potentially prevent street water depths of up to 850 mm (250 mm is the threshold for water nuisance in this research). For this measure, the hydrological effectiveness is assumed to correspond to a volume of 20,000 m³.

5.2.8 Summary Adaptation Measure Portfolio

The hydrological effectiveness, costs, effectiveness-to-cost ratio, and required land area for each measure are presented in Table 4. It is evident that the diversion has the highest hydrological effectiveness. However, together with the infiltration measure, it is also among the most expensive options. Due to these high costs, its effectiveness-to-cost ratio is lower compared to temporary measures or buffer measures.

Among all measures, the temporary barrier at home offers the most favorable effectiveness-to-cost ratio, and it requires no additional land acquisition. The optimization of existing buffers ranks next in terms of cost-effectiveness, although it requires approximately 7000 m² of land. Optimization of the stream, similar to the diversion, has an effectiveness-to-cost ratio of 0.01. The difference is that stream optimization does not require extra land.

Another notable observation is the low effectiveness-to-cost ratio of the infiltration measure, combined with a large additional land requirement of 400,000 m². On the other hand, this is the only measure that strengthens the landscape elements of South Limburg, namely the green character and the balance between open and enclosed spaces.

Table 4 - Adaptation measure portfolio

	Hydrological effectivity (m3)	Costs (€)	Effectivity/costs ratio (m3/€)	Additional area (m2)
Optimization current buffers	20,000	X	X	7000
New buffer location	20,000	X	X	20,000
Temporarily barrier highway	10,000	X	X	0

Infiltration	10,000	X	X	400,000
Diversion	80,000	X	X	30,000
Optimization stream	20,000	X	X	0
Temporarily barrier at home	20,000	200,000	0.1	0

5.3 Adaptation Pathways Voerendaal East

Based on the adaptation measures, a total of 25 adaptation pathways are developed for Voerendaal East, as illustrated in Figure 12. The optimization current buffers measure is included as a no-regret option and serves as the first measure in all adaptation pathways except pathway 25. This pathway consists solely of the diversion measure, which meets the adaptation requirements for all scenarios up to 2150. The costs of this rigid pathway are X and the required land is 30,000 m2.
The optimization current buffers measure was chosen as a no-regret option due to its high effectiveness-to-cost ratio and because responsibility for implementation lies with the Limburg Water Authority. Although the temporary barrier at home measure has the highest effectiveness-to-cost ratio, it is considered undesirable as a baseline measure for the pathways. This is because responsibility would shift directly to homeowners, and additional action would be required during flood events.
The infiltration measure is only required for the most extreme scenario, T200H. This measure requires the acquisition of approximately 400,000 m² of land. Given the large area involved, implementation would take time. Furthermore, the measure would only become effective after a relatively long period, as forest growth is necessary.
For scenarios T25M, T25H, and T50M, the optimization current buffers measure is sufficient until 2150. For T50H and more extreme scenarios, additional measures can be selected after this no-regret option to meet adaptation needs. The choice between the measures depends on which criterion is prioritized.

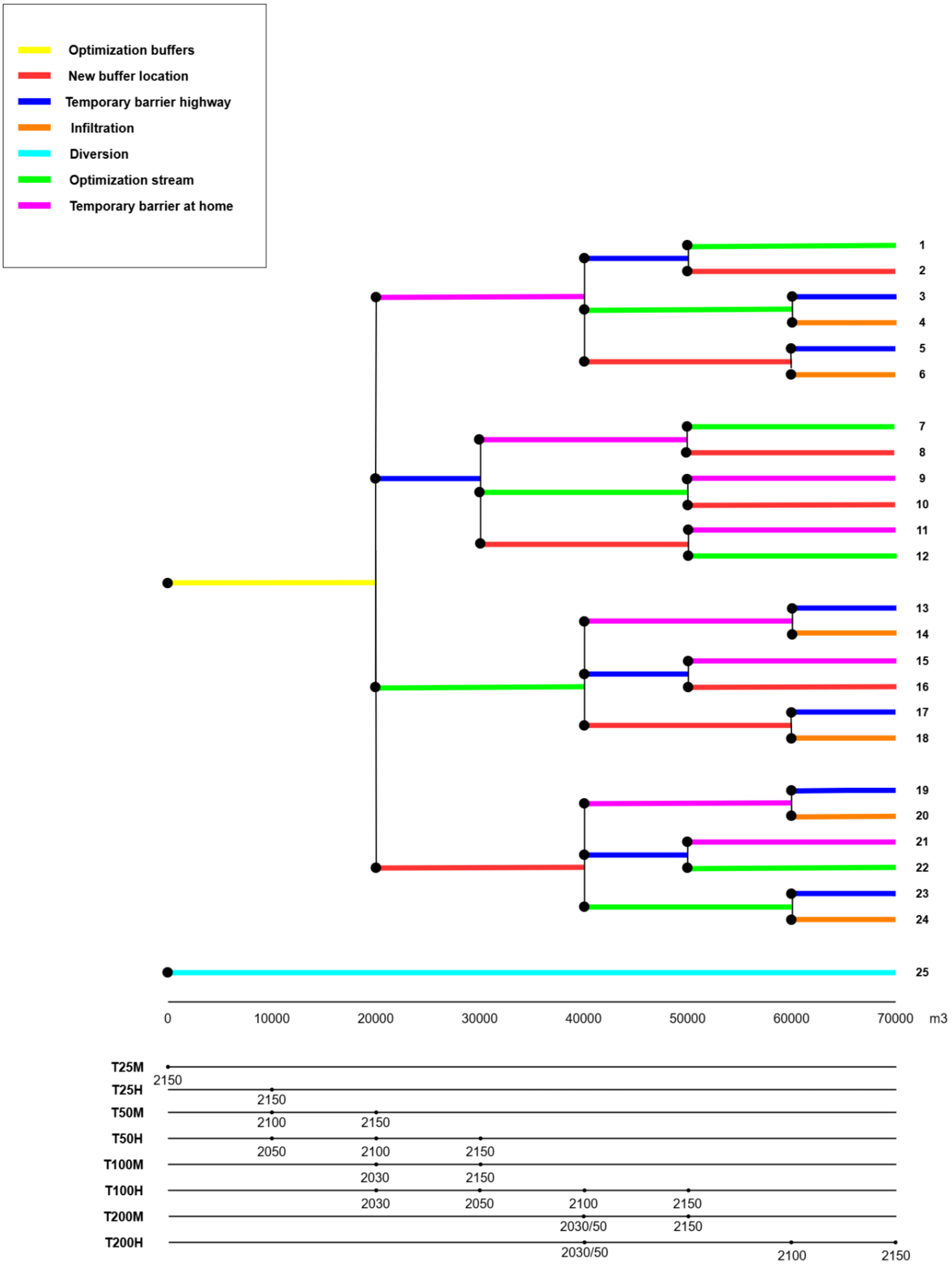

Figure 12 - Adaptation pathways

The total costs and required land through 2150 depend on the adaptation pathway and scenario. Tables 6 and 7 in Annex F present the total costs and the required land through the year 2150. Only

the flexible adaptation pathways are presented in these tables, since the rigid adaptation pathway 25 has one investment in costs and land.
It is notable that all flexible pathways are more cost-effective and require less land for every scenario through 2150 compared to the rigid pathway 25, except when the measure infiltration is implemented. This measure is required for pathways 4, 6, 14, 18, 20, and 24. These pathways are also among the most expensive, along with pathway 25. The cheapest pathways are pathway 2, 5, 8, 11, 19, and 21. These pathways include both temporary measures and the new buffer location measure for the T200H scenario. Pathways 1, 3, 7, 9, 13, and 15 require the least amount of land. The perspectives to select a pathway are presented in Figure 13.

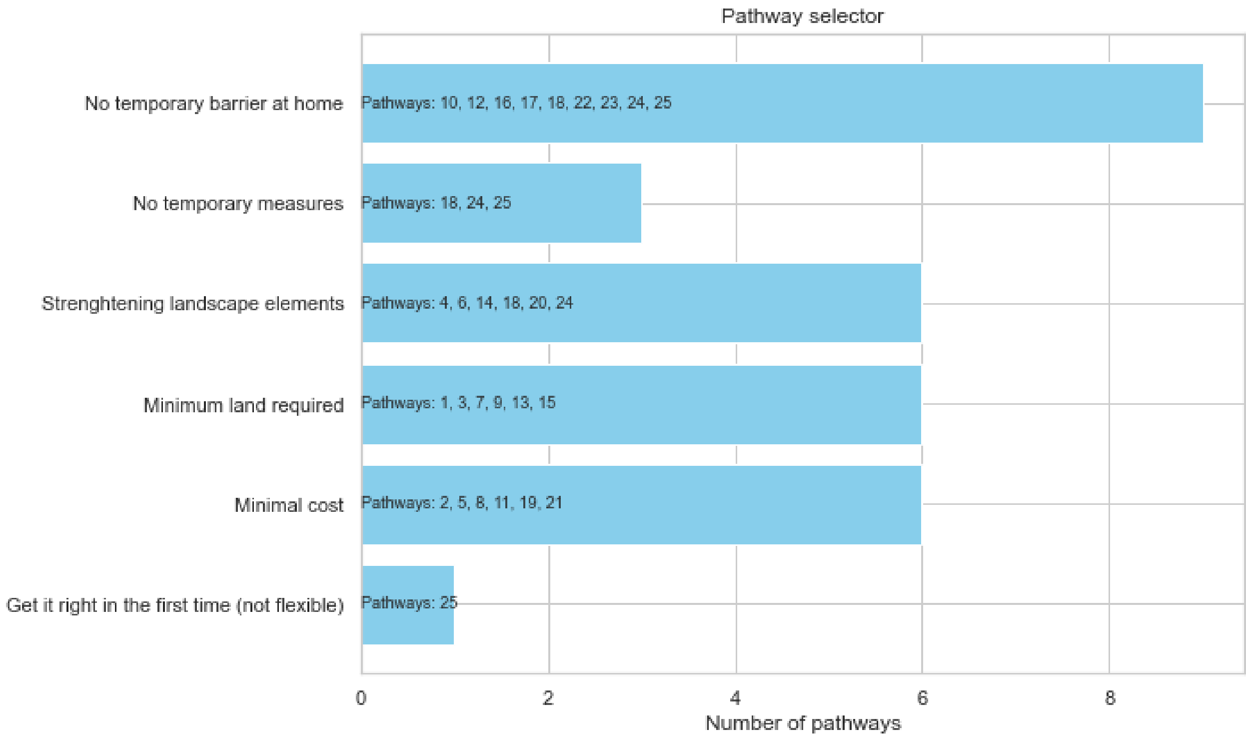

Figure 13 - Adaptation pathway perspectives

6. Discussion

6.1 Trade-offs Pathways

The aim of this research is to provide insight into the costs and spatial integration of different adaptation pathways under extreme precipitation scenarios, in order to manage long-term flood risks in Voerendaal East through 2150. The key findings are 25 adaptation pathways, where the total costs and required land through 2150 depend on the scenario and the pathway itself. The choice of measures is guided by the factor cost, required land, whether the measure is temporary, accountability (with citizens or the water authority), strengthening of landscape elements, or flexibility. This decision depends on the preferences of the stakeholders involved, with Waterschap Limburg being the most influential.

First, a choice can be made regarding whether a measure is temporary. The temporary measures are the cheapest and no land acquisition is required. However, there is a risk that temporary measures may fail during a flood event, for example, if an early warning system malfunctions or barriers are not positioned correctly or in time. Responsibility for implementation also plays a role. It may rest with the water authority or with individual households (e.g., temporary barrier highway versus temporary barrier at home). Households might not be able to install barriers in time, or water could enter through alternative routes such as toilets. If no temporary measures are applied in any scenario, only adaptation pathways 18, 24, and 25 remain. If the temporary barrier at home is excluded, the remaining options are pathways 10, 12, 16, 17, 18, 22, 23, 24 and 25.

Second, a decision can be based on cost. In this regard, the temporary barrier at home is the least expensive measure. If the cheapest measure is always selected, pathways 2, 5, 8, 11, 19, and 21 are prioritized. However, these pathways always include a temporary measure, which carries the risks mentioned above.

Third, a decision can be based on the required land area. If it is desirable to avoid land acquisition, pathways 1, 3, 7, 9, 13, or 15 can be chosen. This may be preferable since not all landowners are willing to sell or exchange their land. If a pathway requiring land acquisition is selected, it may be strategic to choose one where land purchase occurs later in time, allowing for a phased acquisition strategy. For example, the stream optimization measure could be implemented earlier than new buffer location, as the latter requires purchasing 20,000 m² of land.

Landscape integration can also play a role in decision-making. Results show that the infiltration measure is the only one that strengthen current landscape elements. Since this measure requires a large surface area, it has a strong positive effect on landscape integration. If strengthening landscape integration is a priority, adaptation pathways 4, 6, 14, 18, 20, or 24 should be selected. This measure is only necessary for scenario T200H, because time is needed to buy the land and forest growth is necessary.

Finally, flexibility is another factor. Pathway 25 consists solely of the diversion measure, offering no flexibility to switch to other measures. This option could be considered if initial costs and land requirements are not prioritized and the water board wants to be prepared for all scenarios at once. However, if a milder climate scenario develops, the diversion would represent an overinvestment in both cost and land. The overinvestment depends on the chosen scenario and pathway.

6.2 Comparison Adaptation Measures

According to the results of this research, the temporary barrier at home measure is considered the most cost-efficient option. However, it was not adopted as a no-regret measure. This decision is based on the assumption that it is undesirable for Waterschap Limburg to place the responsibility for the first measure in the adaptation pathways on individual citizens. Slager, Becker, Bouaziz, and Kwadijk (2022) argue that this measure is actually advantageous in the short term, as it can be implemented quickly. Asselman and van Heeringen (2023) note that this measure can also increase public awareness of flood risk. According to Asselman & van Heeringen, (2023), such awareness is part of the multi-layered flood safety approach, where awareness is considered layer 0. In addition, it is recommended to combine dry-proofing with wet-proofing measures, for example by replacing wooden floors with tiles. If damage still occurs, an adapted insurance scheme could provide relief. This measure is recommended in situations where inundation does not exceed a few decimeters (Asselman & van Heeringen, 2023).

One finding of this research is that the infiltration measure has a strong strengthening effect on landscape elements, such as the green character and the balance between open and enclosed spaces. The downside of this measure is that costs and land requirements are relatively high. Asselman and van Heeringen (2023) confirm that converting arable land into grassland or forested areas increases infiltration. This measure also enhances the soil's sponge effect and slows surface runoff, which can reduce peak discharge (Slager, Becker, Bouaziz, & Kwadijk, 2022). A co-benefit of this measure is that it strengthens biodiversity and, by improving the soil's sponge effect, also helps mitigate drought issues. If landowners are unwilling to sell land, an intermediate solution could be to increase the organic matter content and soil structure of arable fields. This would improve the soil's sponge effect and reduce runoff (Asselman & van Heeringen, 2023).

The hydrological effectiveness of addressing local bottlenecks (optimization stream in this research), buffering and redirecting water is confirmed by Slager, Becker, Bouaziz, and Kwadijk (2022). These measures could be implemented in the short term. However, it should be noted that these measures offer less co-benefits than nature-based solutions (NbS).

6.3 Implications

According to Asselman and van Heeringen (2023), built-up areas in South Limburg have a protection standard of 1:25, as the costs do not outweigh the benefits. This standard also applies to the urban area of Voerendaal, although a 1:100 standard is desired for built-up areas. The results of this research show that, up to 2150, the diversion measure is hydrologically effective for every scenario, requiring an investment of X and 30,000 m^2 of land. Other, more flexible pathways offer cheaper alternatives, with a minimum total investment of X and 7000 m^2 of land for the most extreme scenario (T200H) up to 2150.

The average cost and land requirement (across all flexible pathways) for achieving a T100 protection standard under a medium climate scenario are X and 12,000 m^2, while under a high climate scenario they are X and 17,000 m^2. When the orographic effect is included in the standard, the average cost for a T200 under the medium scenario is X and 17,000 m^2, and for the high scenario (T200H) is X and 120,000 m^2. The cost variation for pathways under the highest climate scenario is greater than for other scenarios, mainly because the infiltration measure (costing X) is only applied in the most extreme scenario. Pathways that include this measure also require at least 400,000 m^2 of land, however, these pathways strongly strengthen the green character and the contrast between open and closed spaces.

The results indicate that the rigid pathway with the diversion measure represents an overinvestment in both cost and land compared to flexible pathways for all scenarios, except when compared to pathways that include infiltration, which are the most expensive in terms of both cost and land. An additional advantage of not implementing the diversion measure is that 30,000 m² becomes available for housing development, as the planned diversion route runs through a future residential area.

6.4 Limitations

The results of this research should be interpreted with caution. In particular, there is considerable uncertainty in the calculation of the adaptation need, due to the assumptions applied in this research. These assumptions and their limitations are discussed below.

6.4.1 Input Data for Scenarios

The extreme precipitation intensities used in this research are based on the basic statistics of STOWA (2024). These statistics are based on precipitation data from automatic climate stations across the Netherlands. However, the study area is hilly terrain, which affects precipitation events (Forootan, 2023). This means that the precipitation statistics from the stations do not accurately represent the conditions in Voerendaal. Research by Asselman and van Heeringen (2023) indicates that a T1000 event with a precipitation duration of two days in flat terrain may correspond to a T500 event in South Limburg due to orographic effects. Therefore, in addition to the T25 and T100 scenarios in this research, T50 and T200 scenarios are used to partially compensate for the discrepancy in data from flat areas. It should be noted, that this assumption must be interpreted with caution, as this research is based on a precipitation event with a duration of two hours.

6.4.2 Manning's Equation

It is assumed that the floodplain within the urban area functions as a flow path and is considered part of a one-dimensional channel flow. This means that streets are represented as rectangular open channels. The one-dimensional approach (1D) used in this research is based on cross-sections taken perpendicular to the longitudinal direction of the street. It is further assumed that both discharge and water depth remain constant in time. Under these steady-state conditions, the friction slope equals the bed slope, allowing the use of Manning's equation.
Manning's equation is applied to each individual street section, where the mean slope is calculated per section, and the smallest street width is used for the hydraulic calculations.
In practice, discharge and water depth vary over time in a cross-section and in the longitudinal direction. Water travel times vary depending on the topographic location and the surface roughness, which influences hydraulic resistance and flow velocity. These variations lead to peak discharges, which are critical for determining the maximum water depth. When the time-dependent behaviour of flow is considered, including conservation of mass and momentum, the one-dimensional Saint-Venant equations are used.
In a two-dimensional approach (2D), the floodplain is represented as a grid. This method assumes shallow water depths and applies mass and momentum conservation to each grid cell. Discharge, water depth, and velocity are then solved numerically over time. By applying the Saint-Venant equations, peak discharge can be estimated. Moreover, the 2D approach is more capable of capturing hydraulic jumps caused by abrupt changes in geometry. This is particularly important in Voerendaal, where elevation differences, variations in surface roughness, and changes in the wetted cross-sectional profile occur. Therefore the 2D method can estimate discharge and water depth more accurately.

6.4.3 Runoff Model

In this research, runoff is estimated using a runoff coefficient based on slope and land use. These coefficients are determined by the Water Board of Limburg for a precipitation event of 63 mm over two hours. For more extreme precipitation events, different coefficients may be required, as infiltration tends to decrease and runoff increases. This leads to a greater adaptation need.

According to research by Forootan (2023), initial soil moisture conditions and soil type are important factors as well in determining runoff. These additional variables can influence both the volume and timing of runoff and should be incorporated into hydrological modelling. One method that accounts for these variables is the slope-adjusted Curve Number method (Balvanshi & Tiwari, 2014).

While incorporating these variables could improve the model, its binary approach to routing runoff (flow accumulation function) presents an additional limitation. The flow accumulation and flow direction components of the model use a binary, "all-or-nothing" approach to determine the direction of runoff. The flow accumulation function assumes that runoff follows the path of the steepest slope. However, when the momentum of the flow is high, the actual flow path may deviate from this assumption and follow alternative routes. This partly explains the large differences in runoff within the area of impact. According to the verification model, most of the runoff flows straight into the Cortembacherbeek (see Annex B). While the remaining portion flows toward the built-up area of Voerendaal. In contrast, the flow accumulation function assumes that all runoff enters the urban area. As a result, the GIS-based runoff model overestimates runoff in Voerendaal East compared to the verification model.

One would expect water depths, and therefore the adaptation need, to also be overestimated relative to the verification model. However, the calculated water depths based on the runoff results actually underestimate values compared to the verification model. According to the verification model, water depth at the critical adaptation point (measurement point 4) for scenario T100H in the year 2100 should range between 0.8 m and 1.0 m. Using the method applied in this research, the water depth at this location for the same scenario is approximately 0.35 m.

Based on the verification model, it can be concluded that the method used in this research to calculate water depths is not valid. If water depths were calculated using the verification model, this would lead to a higher adaptation need and require additional measures, which would increase costs and possibly the required land area. However, the verification model also indicates that less runoff would pass through the built-up area, which would reduce the adaptation need. The GIS-based runoff model does not account for a sewer system and buffers. This may also partly explain the difference in runoff.

6.4.4 Water Nuisance

Water nuisance is defined based on potential damage to residential buildings. However, as demonstrated during the 2021 flood event, flooding can also cause damage to vehicles, disrupt business operations, impact infrastructure, and lead to agricultural losses (Slager, 2023). The chosen definition of water nuisance directly influences the scale of adaptation required and the timing of tipping points. Therefore, using an alternative definition could result in a lower threshold for water nuisance. As a consequence, the adaptation need would increase, and both adaptation costs and the required land area could increase.

6.4.5 Cost Estimation

The cost estimates in this report are primarily based on WSP's estimates. These estimates include an uncertainty margin, meaning that actual costs are likely to be higher. In addition, maintenance costs and inflation were not considered, which could further increase the total costs.

This research found that the temporary barrier at home measure is the cheapest option. However, each house would require a different protection approach, such as for low-lying garages. Therefore, the actual costs of dry-proofing homes will vary. Water can also find its way through toilets or other openings, which would make this measure more expensive.

6.4.6 Adaptation Criteria

This research has a specific perspective, treating water primarily as a problem, which reflects a single-disciplinary view. However, water challenges are inherently multidisciplinary. For example, the 2018 drought in the Netherlands demonstrated that water issues can impact nature, drinking water supply, and agriculture. A more integrated approach could explore synergies between flood management and water retention.

To increase the value of this research, it would be beneficial to incorporate insights from multiple disciplines when selecting a preferred adaptation pathway. This could be achieved by introducing additional criteria, besides the costs and land requirements. Such an approach would also align with the Water in Balans program, which addresses drought as a key issue. These criteria could be developed in consultation with stakeholders and experts, who could be invited to participate in a co-creation process. Other criteria could also lead to a change in adaptation measures.

6.5 Recommendations

Due to the limitations in determining water depth, it is recommended to calculate runoff and water depths using the verification model to obtain a more realistic estimate of the adaptation need for Voerendaal East under each scenario. This will help assess whether a T100 protection standard for both climate scenarios is achievable through 2150.

Further research is required to determine the impact of orographic effects on extreme precipitation in Limburg and the associated adaptation costs. A long-term monitoring system should be established to measure precipitation and runoff in the hilly landscape of Voerendaal. These data will provide a basis for more accurate predictions of extreme precipitation intensities in hilly areas. Additionally, geology and initial soil moisture content are important parameters for predicting runoff, which were not included in this research. Further research is needed to assess their influence on the hydraulic response of the catchment.

The runoff coefficients used in this research are based on an intensity of 63 mm, while most scenarios involve more extreme intensities. Additional research is necessary to determine the effect of higher precipitation intensities on runoff coefficients.

Integrating multidisciplinary criteria in pathway selection: adaptation pathways should be evaluated not only on cost and land requirements but also on additional criteria such as drought resilience. These criteria should be aligned with the Water in Balans program and developed in consultation with stakeholders and experts to ensure coherence and support.

7. Conclusion

In this chapter, the research questions are addressed. To answer the main question, the sub-questions are first discussed:

How do future extreme precipitation scenarios influence the adaptation need for Voerendaal East?

Eight extreme precipitation scenarios are analysed, combining four return periods (T25, T50, T100, T200) with medium and high climate scenarios. The adaptation need of Voerendaal East is defined as the runoff volume that exceeds a water depth threshold of 0.25 m within a two-hour period at street level at the critical adaptation point. This point represents the location along the main runoff streamline where the maximum water depth occurs within the area of impact, which is the part of the catchment from which runoff converges toward the built-up area.
Under high scenarios, the adaptation need increases faster over time than under medium scenarios, following the same trend as extreme precipitation intensities. For T25M, no measures are required through 2150, while T25H reaches 10,000 m³ by 2150. T50 scenarios require action immediately (starting at 10,000 m³), T100 starts at 20,000 m³, and T200 at 40,000 m³. The highest need occurs under T200H in 2150, reaching 70,000 m³.

What measures are hydrologically effective for managing extreme precipitation, and what are their associated costs and spatial integration requirements?

Seven hydrologically effective measures are identified: optimization of current buffers, new buffer locations, temporary barrier at home, temporary barrier highway, diversion, stream optimization, and infiltration. The dams upstream measure is excluded due to its weakening impact on landscape elements. The measure diversion provides the highest hydrological effectiveness, with a capacity of approximately 80,000 m³. The effectiveness of the other measures is 10,000 m³ or 20,000 m³.
In terms of cost, temporary measures (barriers at home and highway) are the least expensive, followed by buffer optimization and a new buffer location. Stream optimization is estimated at X, while infiltration and diversion are the most costly, each at X.
Spatial integration is assessed based on the land area required for implementation, as this influences both stakeholder support (due to land acquisition) and landscape impact. Temporary measures and stream optimization require no additional land, buffer optimization requires 7000 m², diversion 30,000 m², and infiltration 400,000 m². Despite its large land requirement, infiltration strengthens effect on the landscape elements of the South Limburg hill country. This includes the strengthening of the green character and the balance between open and enclosed spaces.

The main research question of this research is:

What are possible adaptation pathways for Voerendaal East to manage future extreme precipitation through 2150, considering hydrological effectiveness, costs, and spatial integration?

In this research, 25 adaptation pathways are developed based on the measures to enable adaptive responses to the deep uncertainty surrounding long-term extreme precipitation. A preferred pathway can be selected based on the following perspectives:

- Cost minimization
- Minimization of required land
- Avoidance of temporary measures
- No temporary barrier at home
- One-time measure ("get it right the first time", the diversion)
- Strengthening landscape elements

The optimization current buffers measure emerges as the preferred initial action for all pathways. This measure scores well in terms of both costs and required land and is not a temporary measure.
It is notable that all flexible pathways are more cost-effective and require less land across all scenarios through 2150 compared to the rigid Pathway 25 (the diversion), except for pathways where the infiltration measure is applied. This research highlights the importance of adaptive planning in and around urban areas located in hilly regions to manage long-term flood risk induced by extreme precipitation.

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Appendix A – Data Action Model GIS-based Runoff Model

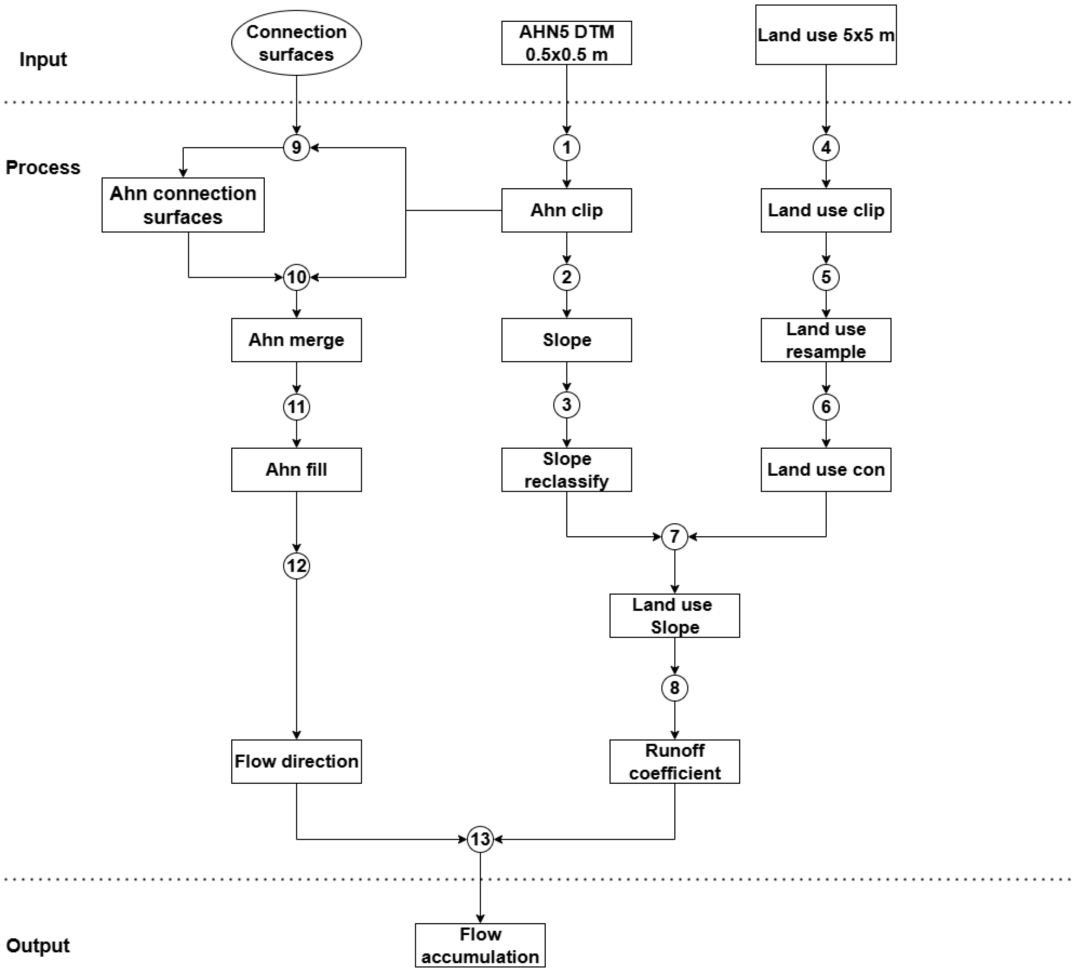


Figure 14 - Data action model GIS-based runoff model

1. Raster calculator
2. Slope
3. Reclassify
4. Resample
5. Raster calculator
6. Raster calculator
7. Raster calculator
8. Raster calculator
9. Zonal statistics
10. Raster calculator
11. Fill
12. Flow direction
13. Flow accumulation

Appendix B – GIS Maps

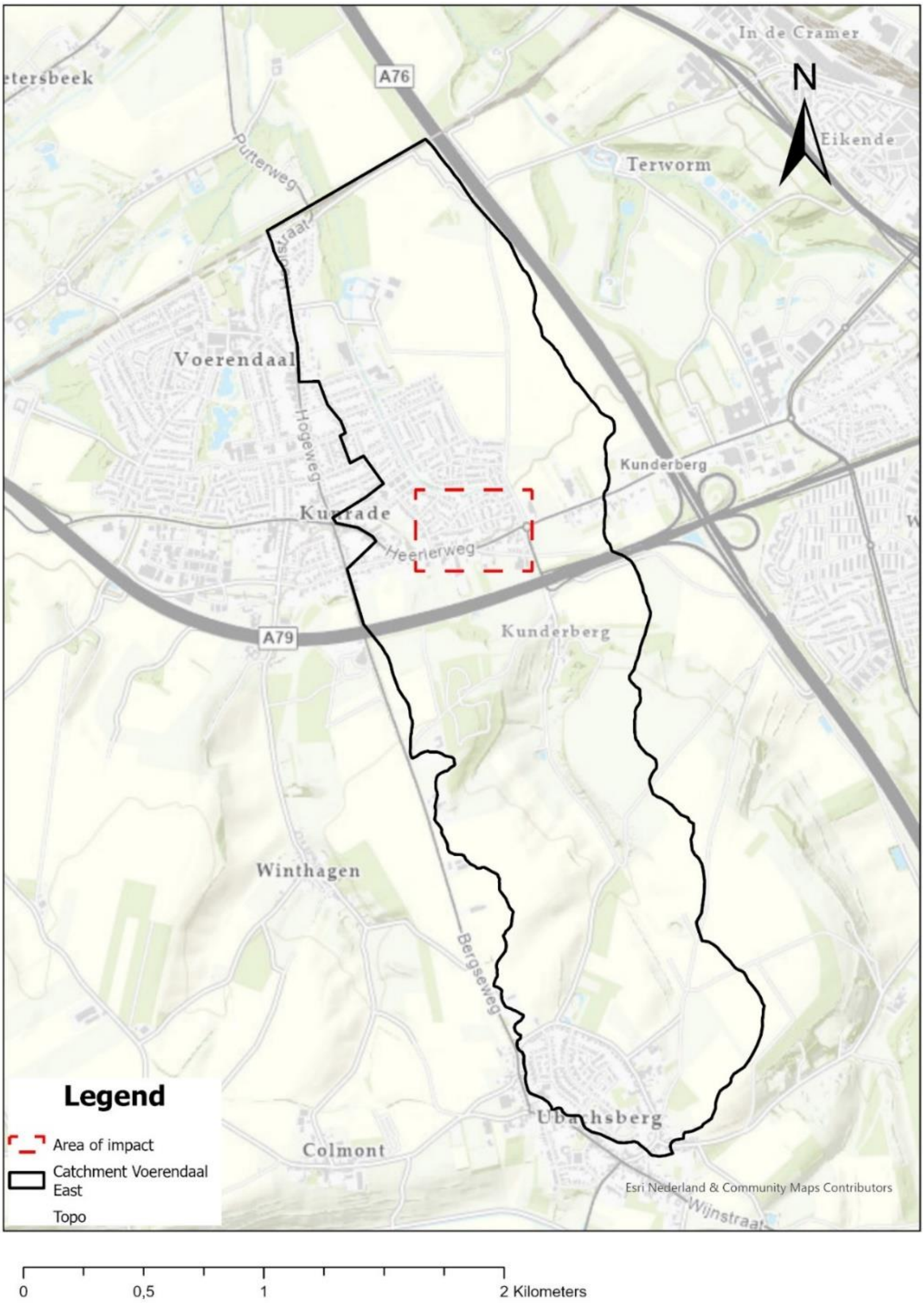


Figure 15 - Area of impact (zoomed out)

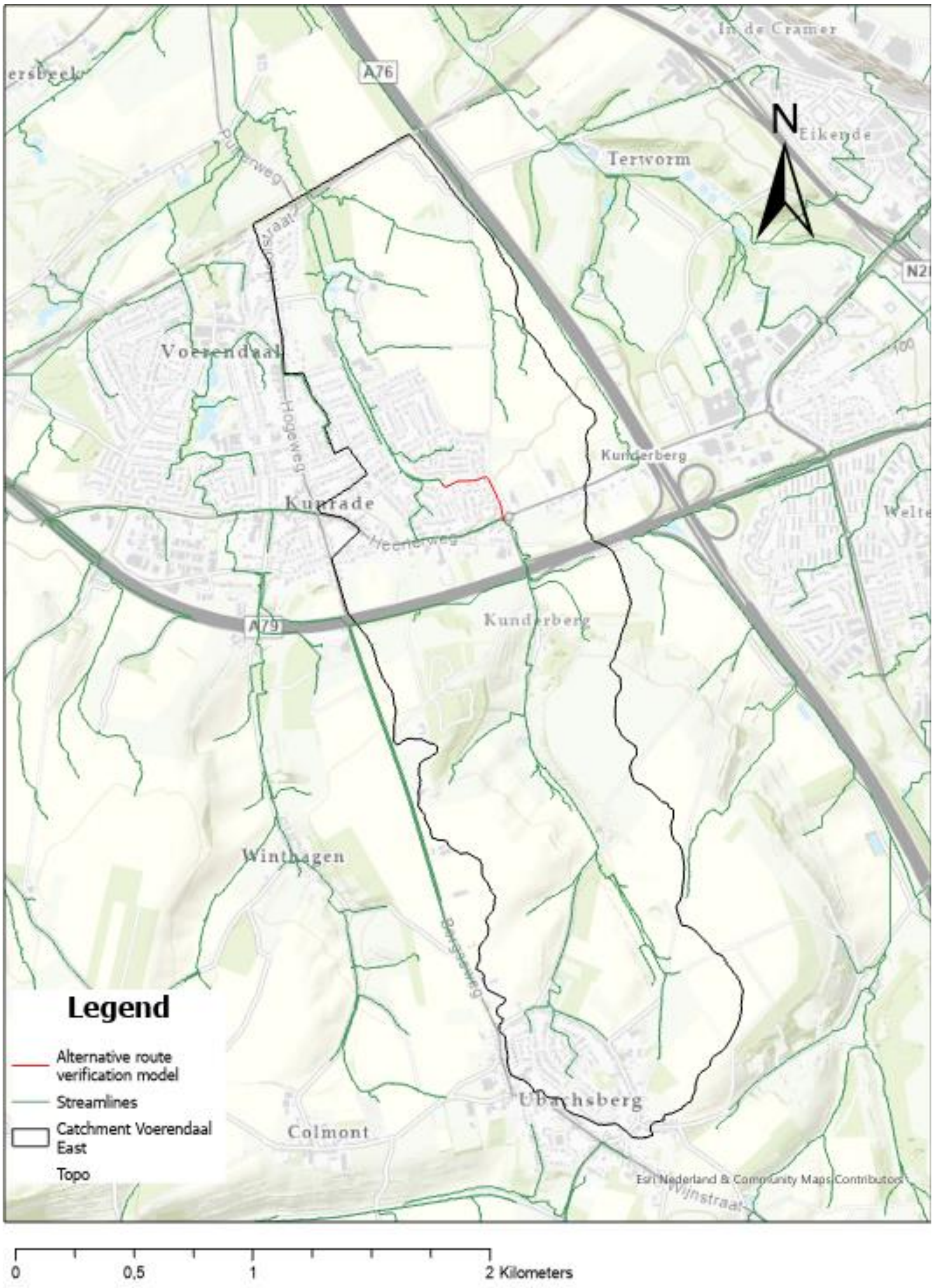


Figure 16 - Streamlines (green) and streamline route verification model (red)

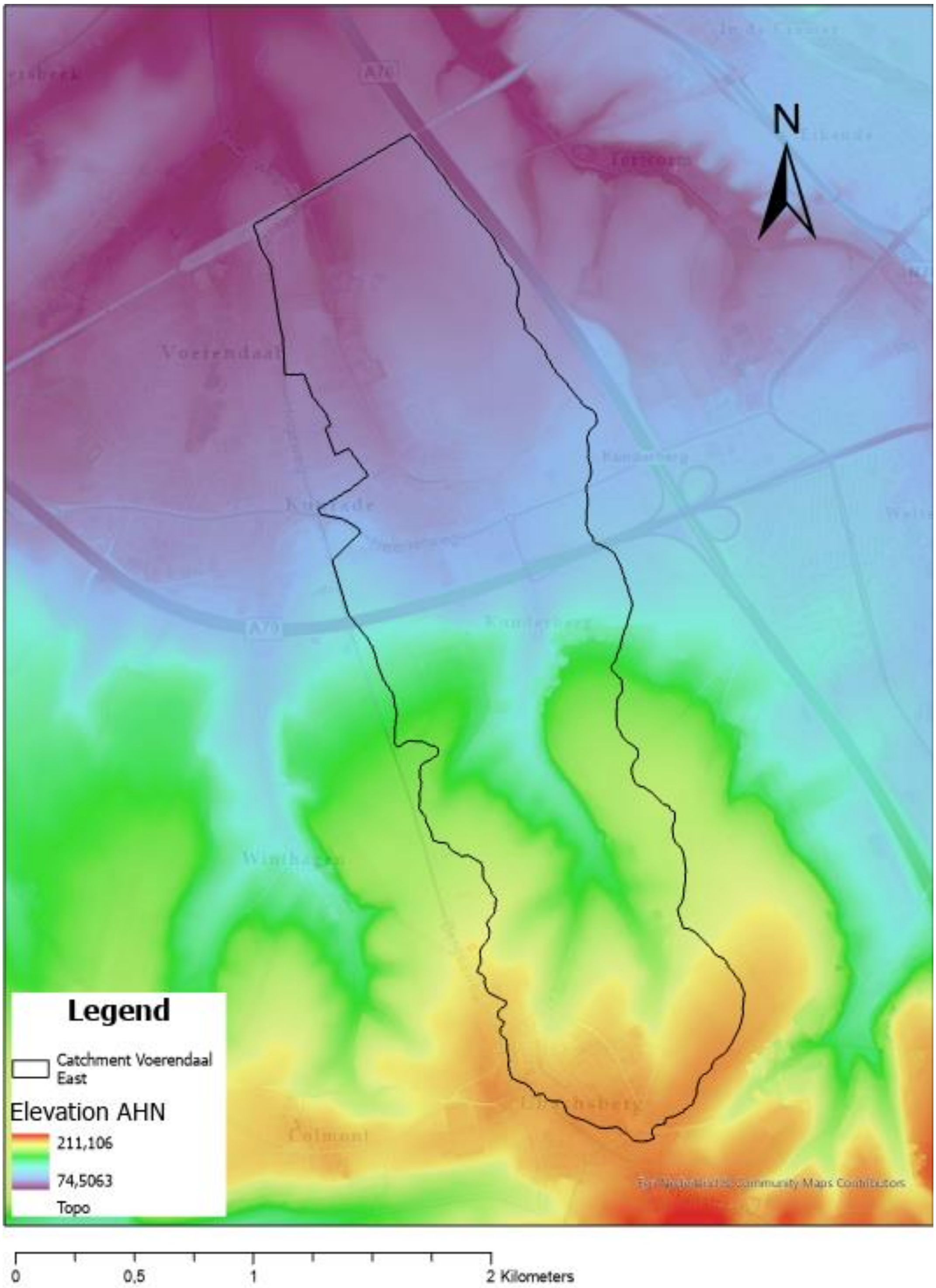
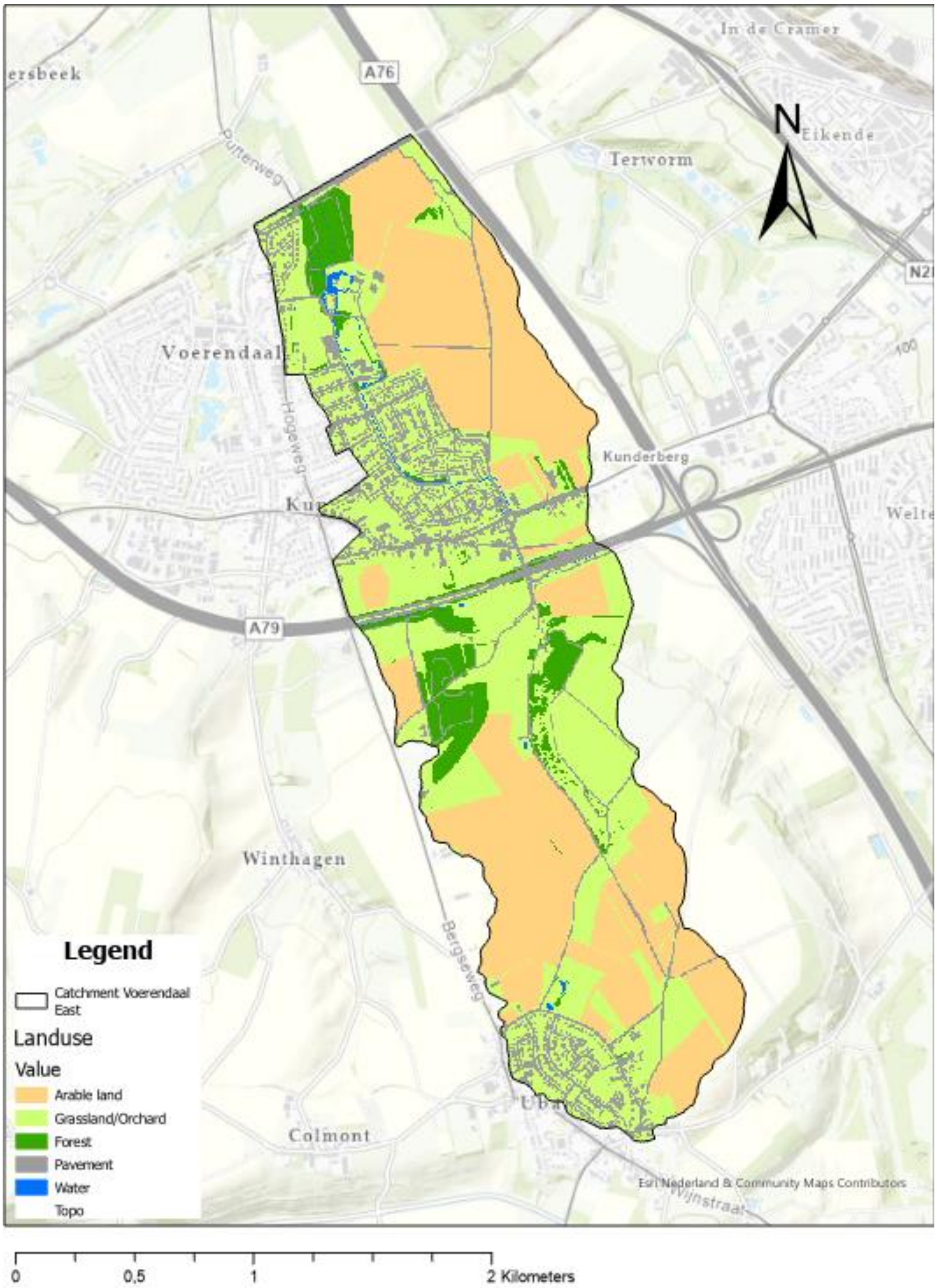


Figure 17 - Elevation (in meters) AHN5


Legend
Catchment Voerendaal East
Landuse
Value
Arable land
Grassland/Orchard
Forest
Pavement
Water
Topo
N
Voerendaal
Terworm
Kunderberg
Winthagen
Colmont
A76
A79
Bergseweg
Hogeweg
Putterweg
Esri Nederland & Community Maps Contributors
0
0,5
1
2 Kilometers

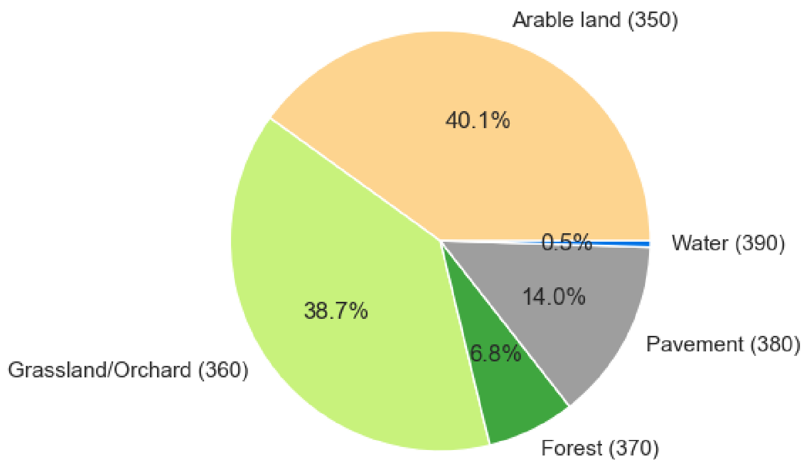


Figure 18 - Land use of the catchment

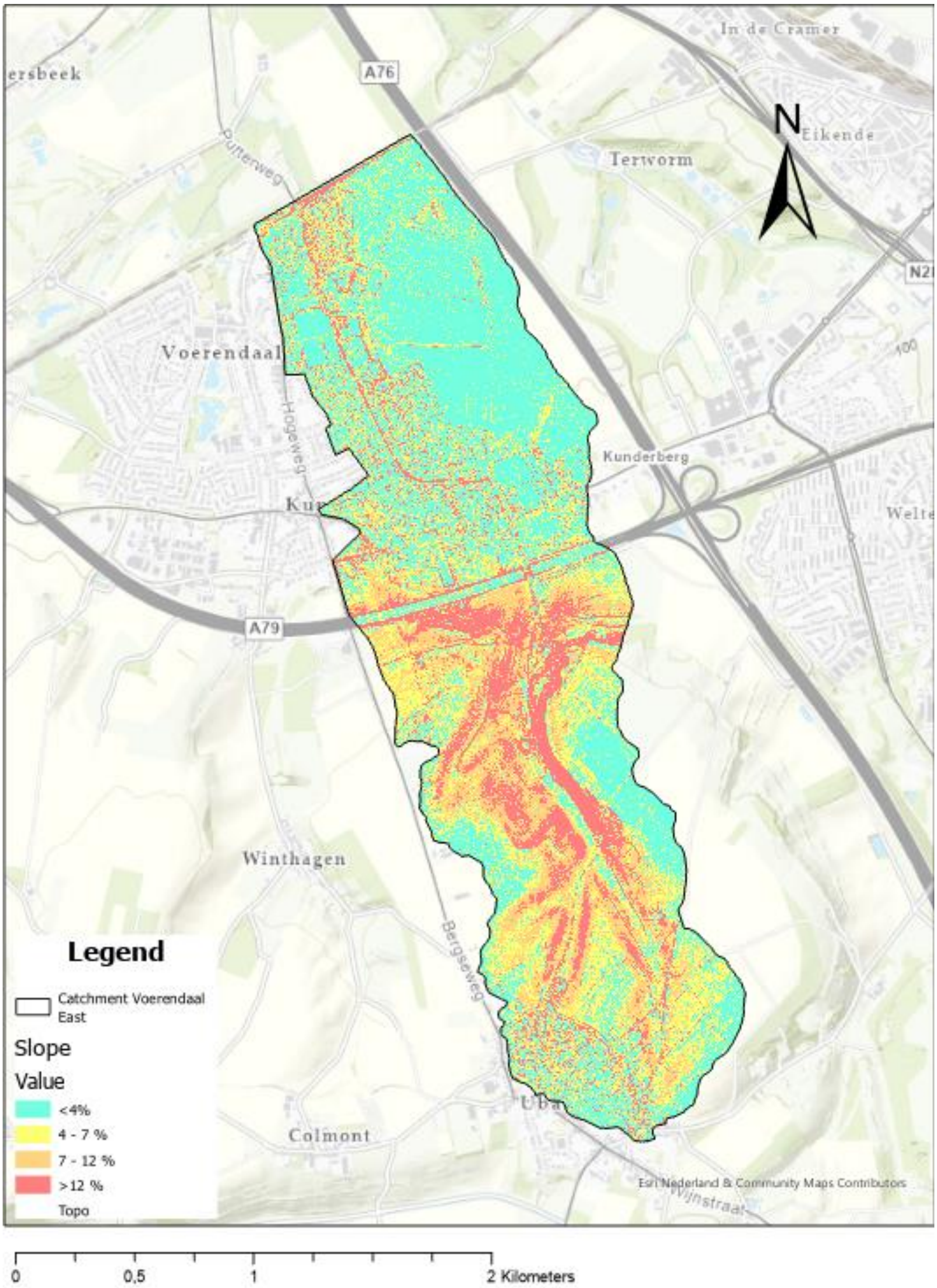


Figure 19 – Slope percentage of the catchment

Appendix C – Verification GIS-based Runoff Model

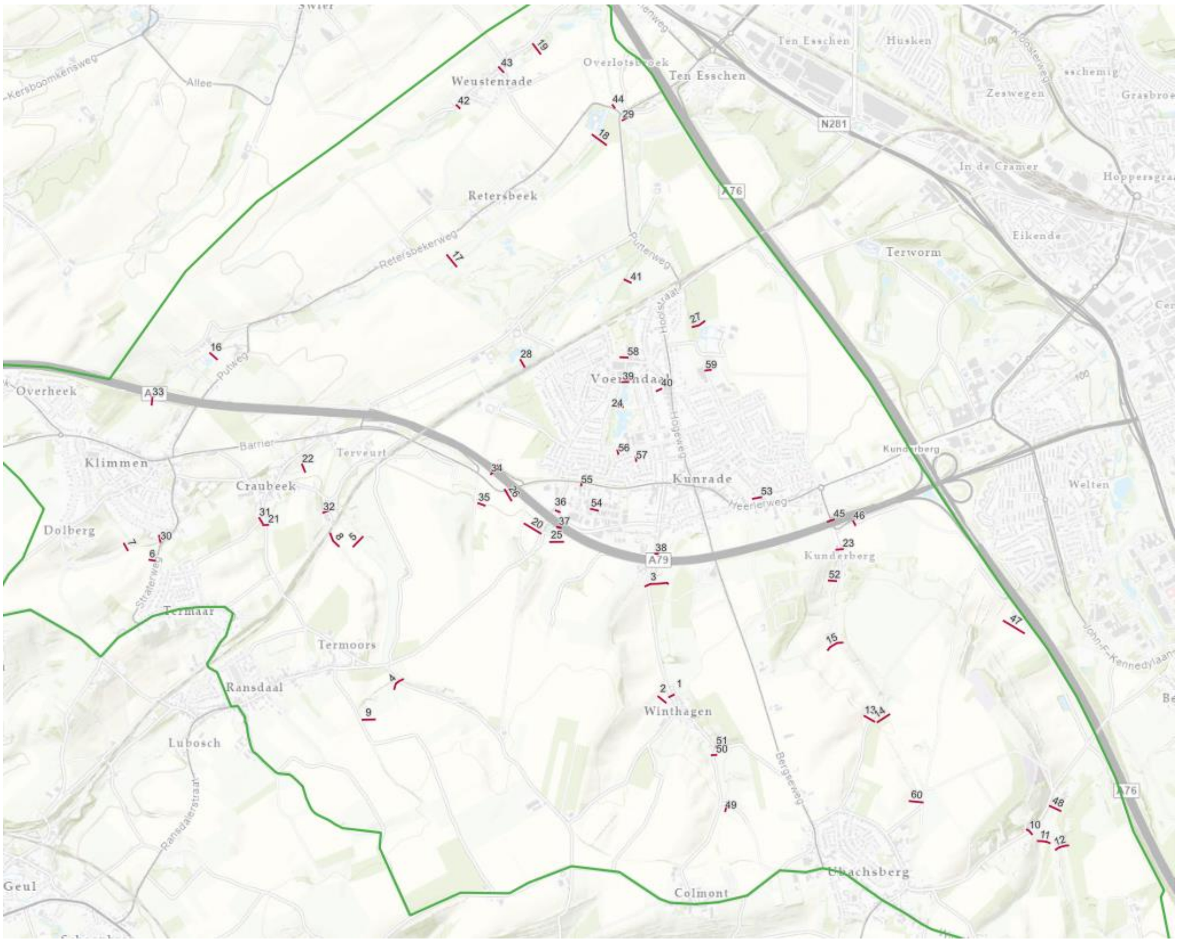


Figure 20 - Verification points

ID	Toelichting	Sweco_T10	Sweco_T25	Sweco_T100		T25	T100			T25	T100
1	Winthagen1	8532	18185	41518							
2	Winthagen2	13210	20249	35997		17228	25087			0,85080804	0,69691181
3	buffer_Winthagerweg	34963	59596	114972						0	0
4	buffer_Karstraat	12225	20920	40598		19776	28612			0,94531119	0,70476376
5	Keldervloedgraaf	18154	34653	74813						0	0
6	Straterweg	3156	5145	9760						0	0
7	Kickenbroekerweg	5196	8308	15273						0	0
8	Dr Kelder	4511	6811	11970		5346	7780			0,78495218	0,64996426
9	Karstraat2	2007	3864	7996						0	0
10	De Putberg West	6053	9917	18696		9789	14254			0,98705754	0,76239084
11	De Putberg Midden	8894	14044	25855						0	0
12	De Putberg Oost	7497	12532	23957		12580	18320			1,00383941	0,76471872
13	Kersboomkensweg	6953	12209	24693						0	0
14	Kunderberg boven	8283	13857	26695		14372	20928			1,0371687	0,78397667
15	Kunderberg buffer	21196	35300	68251						0	0
16	Retersbeek boven	6344	12489	26764						0	0
17	Retersbeek midden	20526	40501	86610						0	0
18	Retersbeek beneden	15233	38959	102091						0	0
19	Luiperbeek	5974	17563	47197						0	0
20	Midweg	3901	6395	11077		9002	12979			1,40775513	1,17173168
21	Penderskoolhofweg_zuid	3061	4772	8676		4413	6426			0,9247879	0,74064264
22	Caubekerstraat	10696	21791	45189						0	0
23	Kunderberg_voor A79	18503	37100	81700						0	0
24	Mergelweg	15117	39718	88162						0	0
25	Midweg Oost	7165	11489	21112		11137	16217			0,96938697	0,76814738
26	Valkenburgerweg	5051	7897	14341						0	0
27	Cortenbacherbeek	14934	43725	110663						0	0
28	Hoenspad	17752	25343	37437						0	0
29	Geleenbeek	369	5358	30197						0	0
30	Kickenbroekbroekerweg_ben	5677	10784	22183						0	0
31	Penderskoolhofweg_west	1939	2926	5190		2492	3630			0,85153437	0,69937265
32	Peerboomkensweg	21031	41449	91359						0	0
33	A79_zuidwest	4983	7228	11805						0	0
34	A79_midden	16092	27947	54783						0	0
35	Barrier	4963	8425	17280						0	0
36	Midweg_ben	690	735	808						0	0
37	Midweg_A79	5391	9439	17022						0	0
38	Op de Beek	16523	35523	77326						0	0
39	Dammerscheyd_ben	2631	28035	84058						0	0
40	Keerberg_achtertuin	68	215	3038						0	0
41	Sabinapad	25591	38071	37238						0	0
42	Luiperbeekstraat_bov	5176	15227	37753						0	0
43	Luiperbeekstraat_ben	98	87	18633						0	0
44	Retersbeek	3032	25585	76826						0	0
45	Kunderberg_naA79	17314	38091	86633						0	0
46	A79_zuidoost	1258	2216	4360						0	0
47	Rietjensdalerweg_buffer	5175	8520	14981						0	0
48	De Putberg_ben	16640	32088	66922						0	0
49	Duivenweg	2602	3994	7072		3385	4929			0,84757306	0,69696373
50	Wachelderberg_bov	12299	19324	35266		20175	29378			1,0440392	0,83303276
51	Wachelderberg_oost	1957	3191	6023		2758	4017			0,86432184	0,66698912
52	Kunderberg_midden	17899	36949	78720						0	0
53	Kundergats	8978	18544	35970						0	0
54	Linderlaufer Gewande	32	354	5605						0	0
55	Lindelaufer Gewande2	311	450	837						0	0
56	Skatebaan	62	1862	5172						0	0
57	Van Elmptstraat	3819	11121	23348						0	0
58	Kerkplein	8	7212	27758						0	0
59	Hongerbeek	14465	41416	103274						0	0
60	Ulbachsberg	2075	3804	7827		4404	6377			1,15777619	0,81475383
								Gem		0,97687941	0,76816856
										T25	T100
								Sd		0,15328549	0,12346308

Figure 21 – Verification (only for the points upstream of the cathment, without influence of buffer/sewer)

Appendix D – Critical Adaptation Point

Table 5 - Measurement points critical adaptation

Measurement point	Slope (-)	Width (m)	Flow accumulation (-)	Water level (m)
1	0.007	25	4299314	0.23
2	0.006	23	4325288	0.25
3	0.009	13	4525203	0.32
4	0.005	10	4417050	0.46
5	0.01	16	4689739	0.29
6	0.004	14	4710148	0.41
7	0.004	13	4813141	0.44
8	0.01	15	4822430	0.30

Appendix E – Co-Creation Results

Group 1

Rural adaptations:

- Buffer (see point 3,4,5)
- Infiltration (Replace fields with forest)
- Water collection (on each field)
- Water collection underneath roads
- Redesign stream/stream valley. Dam system in the valley in combination with big buffers

Urban adaptations:

- Diversion (partly rural). Possible with a wall or canal
- Build on mound (elevation)
- Redesign roads (elevation) or car free road. To divert water (So could be part of point 6)
- Water collection underneath roads (see also point 13)
- Water collection roofs/gardens/underneath house or garden
- Urban water buffers
- Water infiltration (de-tile)
- Underground rainwater system
- Redesign stream/stream valley. Expand current capacity canal/stream (Solving bottlenecks).
- Divert water into the current stream. Tunneling is an option.

Group 2

Rural adaptation:

- Buffers; Expand current buffers
- Buffers; Add new buffer location

Urban adaptation:

- Diversion
- Solve urban bottlenecks
- Temporary barrier viaduct; Dike system- highway as dike (A79)

Appendix F – Costs and Land Requirements per Adaptation Pathway in 2150

Table 6 - Costs pathways 2150

Costs (€)	T25M	T25H	T50M	T50H	T100M	T100H	T200M	T200H
1	0	700000	700000	900000	900000	1400000	1400000	3400000
2	0	700000	700000	900000	900000	1400000	1400000	2400000
3	0	700000	700000	900000	900000	2900000	2900000	3400000
4	0	700000	700000	900000	900000	2900000	2900000	8900000
5	0	700000	700000	900000	900000	1900000	1900000	2400000
6	0	700000	700000	900000	900000	1900000	1900000	7900000
7	0	700000	700000	1200000	1200000	1400000	1400000	3400000
8	0	700000	700000	1200000	1200000	1400000	1400000	2400000
9	0	700000	700000	1200000	1200000	3200000	3200000	3400000
10	0	700000	700000	1200000	1200000	3200000	3200000	4200000
11	0	700000	700000	1200000	1200000	2200000	2200000	2400000
12	0	700000	700000	1200000	1200000	2200000	2200000	4200000
13	0	700000	700000	2700000	2700000	2900000	2900000	3400000
14	0	700000	700000	2700000	2700000	2900000	2900000	8900000
15	0	700000	700000	2700000	2700000	3200000	3200000	3400000
16	0	700000	700000	2700000	2700000	3200000	3200000	4400000
17	0	700000	700000	2700000	2700000	3700000	3700000	4200000
18	0	700000	700000	2700000	2700000	3700000	3700000	9700000
19	0	700000	700000	1700000	1700000	1900000	1900000	2400000
20	0	700000	700000	1700000	1700000	1900000	1900000	7900000
21	0	700000	700000	1700000	1700000	2200000	2200000	2400000
22	0	700000	700000	1700000	1700000	2200000	2200000	4200000
23	0	700000	700000	1700000	1700000	3700000	3700000	4200000
24	0	700000	700000	1700000	1700000	3700000	3700000	9700000

Table 7 - Land requirements pathways 2150

Area (m2)								
	T25M	T25H	T50M	T50H	T100M	T100H	T200M	T200H
1	0	7000	7000	7000	7000	7000	7000	7000
2	0	7000	7000	7000	7000	7000	7000	27000
3	0	7000	7000	7000	7000	7000	7000	7000
4	0	7000	7000	7000	7000	7000	7000	407000
5	0	7000	7000	7000	7000	27000	27000	27000
6	0	7000	7000	7000	7000	27000	27000	427000
7	0	7000	7000	7000	7000	7000	7000	7000
8	0	7000	7000	7000	7000	7000	7000	27000
9	0	7000	7000	7000	7000	7000	7000	7000
10	0	7000	7000	7000	7000	7000	7000	27000
11	0	7000	7000	7000	7000	27000	27000	27000
12	0	7000	7000	7000	7000	27000	27000	27000
13	0	7000	7000	7000	7000	7000	7000	7000
14	0	7000	7000	7000	7000	7000	7000	407000
15	0	7000	7000	7000	7000	7000	7000	7000
16	0	7000	7000	7000	7000	7000	7000	27000
17	0	7000	7000	7000	7000	27000	27000	27000
18	0	7000	7000	7000	7000	27000	27000	427000
19	0	7000	7000	27000	27000	27000	27000	27000
20	0	7000	7000	27000	27000	27000	27000	427000
21	0	7000	7000	27000	27000	27000	27000	27000
22	0	7000	7000	27000	27000	27000	27000	27000
23	0	7000	7000	27000	27000	27000	27000	27000
24	0	7000	7000	27000	27000	27000	27000	427000

Appendix G – AI Use Statement

During the writing of this research, the author used Microsoft Copilot to improve grammar and spelling and to support brainstorming. After using this tool, the author reviewed and edited the content as needed and takes full responsibility for the final publication.