Master's Thesis - master Water Science and Management

# REPROFILING WATERCOURSES TO INCREASE GROUNDWATER LEVELS & MITIGATE DROUGHT


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# ABSTRACT

Increasing temperatures and changing precipitation patterns due to climate change are affecting the fresh water availability and causing drought issues globally. The increased drought severity is affecting the livelihoods of people and causing significant economic damage. The elevated sandy soils of The Netherlands are especially affected by the increased drought issues due to the soil composition, elevation, climate and little fresh water inflow. The increased pressure on the fresh water availability due to the changing climate results in declining groundwater levels affecting nature and agricultural areas. The current body of literature on modelling drought mitigation measures is however limited. Therefore this thesis is focused on analysing the effect of drought mitigation measures, in specific reprofiling watercourses, on groundwater levels.

The effect of reprofiling watercourses in the elevated sandy soils of The Netherlands was analysed by applying the groundwater model Amigo on the study area Winterswijk. The effect of reprofiling primary or secondary watercourses were analysed as well as the combined effect of reprofiling both watercourses. Additionally, an analysis has been performed on the effect it has on the agricultural and nature areas. The effect of reprofiling watercourses were analysed based on groundwater characteristics in order to quantify the impact.

Raising the river bed and water level of primary watercourses was shown to be most effective in the whole area of Winterswijk but also specifically in the agricultural and nature area. Raising the river bed and water level of both primary and secondary watercourses simultaneously was shown to be overall most effective. The effectiveness of reprofiling either primary or secondary watercourses depend on the water system. A shallow water system dominated with secondary watercourses experiences more effect from reprofiling secondary watercourses. All in all raising the river bed and water level of watercourses while maintaining the same drainage volume resulted in a significant increase of groundwater levels and great contribution to drought mitigation.

While groundwater models are mere a simplification of reality, the results were supported by literature and provided valuable insights for future water management strategies. Nevertheless, reprofiling measures can mitigate drought but also increase nuisance. Therefore, further research is required on different reprofiling measures to find a balance between drought mitigation and preventing nuisance.

*Keywords*: Drought; Mitigation; Redesigning; Water system; Groundwater; Modelling

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# 1. INTRODUCTION

In recent years droughts became more frequently and severe on a global scale and as a consequence affected millions of people (Spinoni et al., 2013; Dai, 2010). Due to global population growth and subsequently growing agricultural, energy and industrial sectors the pressure on the already limited fresh water availability increases (Mishra & Singh, 2011). Additionally, climate change and water contamination contribute to limiting this fresh water availability resulting in increased drought issues (Mishra & Singh, 2011). According to Spinoni et al. (2013), two billion people globally were affected and eleven million people were killed by drought disasters between 1900 and 2011. In Europe the increase in drought severity, frequency and duration happened more recently the last decades (Spinoni et al., 2013). Subsequently, according to Mishra and Singh (2010), this resulted in a yearly average economic impact from 1991 until 2007 in Europe of €5.3 billion and the drought of 2003 resulted in at least €8.7 billion damage. The Netherlands is no exception to the increasing problems surrounding drought. The period from 2018 until 2020 is identified as a long-term drought and the year 2022 is in the top 5% of driest years since 1906 (Van der Wiel & Wanders, 2022). The economic damage in 2018 was estimated between €450 and €2080 million (Philip et al., 2020). The maximum precipitation shortage reached in 2018 was 309 mm which has an recurrence period of 30 years based on statistical analysis (Sluijter et al., 2018). Therefore, the need for/interest in research exploring droughts and drought mitigation measures is increasing. In specific the potential of mitigating drought impacts via adaptations of the water system has received significant interest the Dutch water management community. Drought mitigation measures can be categorized as follows: 1) increase supply, 2) reduce demand, and 3) minimize drought impact (Vogt & Somma, 2000). This study focusses on increasing the supply of water in the growing season in the area of The Achterhoek through reprofiling the watercourses and decreasing drainage.

The elevated sandy soils in the east of The Netherlands, such as The Achterhoek as seen in Figure 1-1, are especially affected by the impacts of drought because of several aspects. Firstly, the streams in this area provide minimal fresh water inflow. Therefore, the area relies on groundwater extractions, precipitation and soil moisture for irrigation, drinking and industrial water (Klijn et al., 2012), (Smeets et al., 2009).

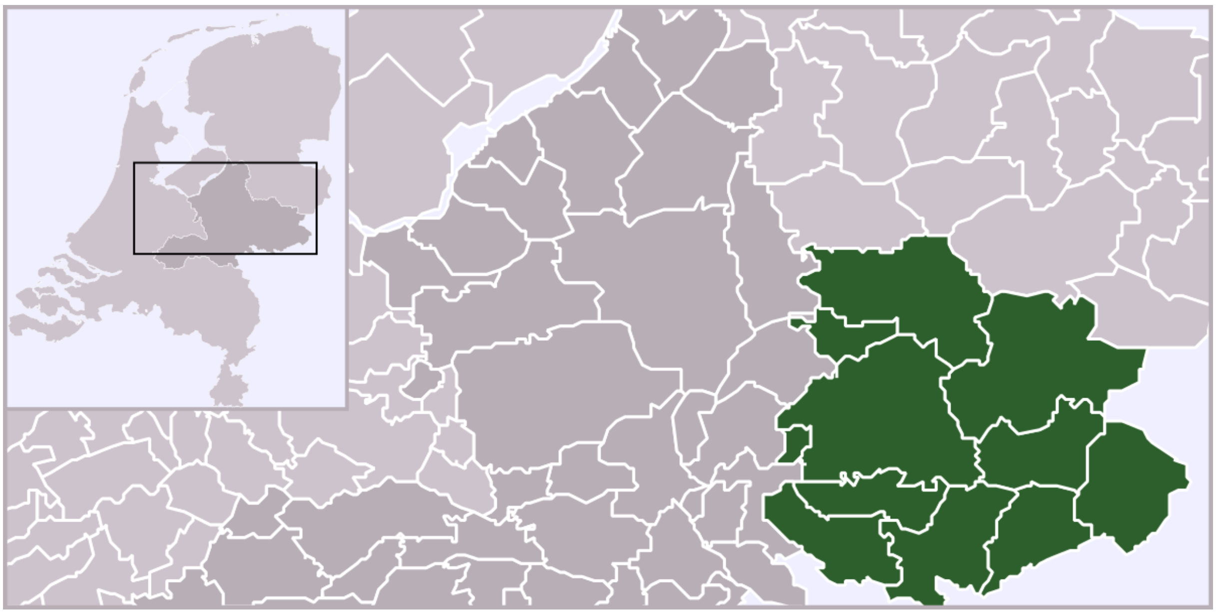

*Figure 1-1 The region The Achterhoek in The Netherlands, (Wikipedia-bijdragers, 2023)*

Secondly, the increased elevation of this area discommode the possibility to maintain a water level. The ditches are being fed by the main streams instead of the ditches draining to the main streams, as is the case for the lower lying west of The Netherlands (Klijn et al., 2012). Additionally, the mainly sandy soils contribute to increased drainage as the sand is characterized by relatively large hydraulic conductivity and low suction with regards to other types of soil (Hendriks, 2010). Therefore, the sandy soils do not retain much water. Lastly, the climate in this area relates more to a continental climate in comparison to other areas in The Netherlands, which translates to hot summers, cold winters and little rainfall, which is currently amplified by climate change (Dommenget, 2009). The spatial difference in climate can be seen in Figure 1-2, the trend of precipitation decreases in the east of The Netherlands while temperature, radiation and PET[1] increases. The combination of less precipitation but more radiation and PET increases the precipitation deficit and amplifies drought issues in the Achterhoek which is also confirmed by Daniels et al. (2013). Following the above mentioned trends the sandy soils in The Netherlands experience severe groundwater droughts (Van den Eertwegh et al., 2021). Therefore, this study will focus on mitigating groundwater drought.

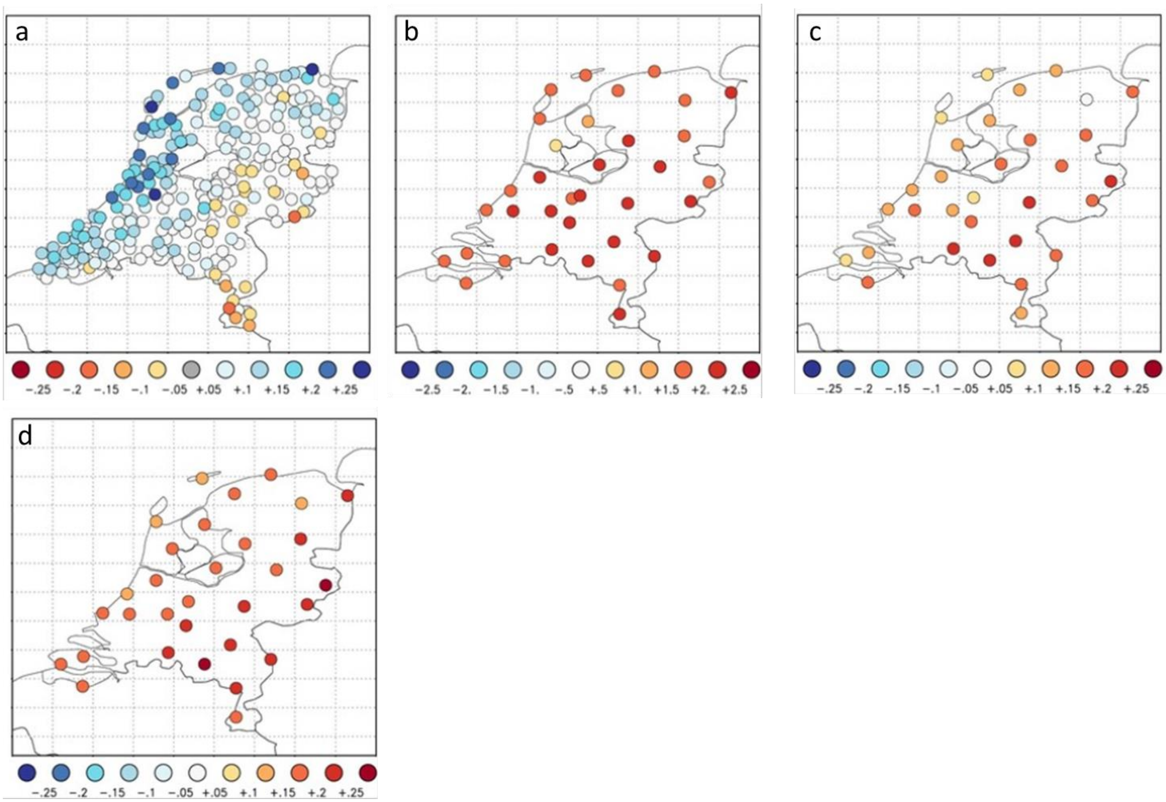


*Figure 1-2 Regression trends of the smoothed average temperature between April and September related to a) precipitation (fraction/K), b) temperature (K/K), c) radiation (fraction/K) and d) Makkink PET (fraction/K), (Adjusted from Philip et al., 2020. The trends are defined as the regression of the variables against the smoothed global average temperature (Philip et al., 2020). The global temperature has increased approximately 1 degree since 1950, therefore this also represents the trend over 1 degree increase due to climate change (Philip et al., 2020).*

[1] Potential Evapotranspiration. The Makkink PET originates from a radiation based equation using the air temperature and the incoming shortwave radiation at earth's surface, which is used often and performs well in The Netherlands (Hendriks, 2010).

## 1.1 State of the art in drought mitigation modelling

The current status of literature on groundwater drought mitigation by means of reprofiling watercourses in The Netherlands is limited. A few studies have been conducted with similar problem definitions and study areas, namely drought mitigation through watercourse reprofiling in the elevated sandy soils in the Achterhoek. Querner and Van Lanen (2001) studied the effect of two types of drought mitigation measures on two adjacent and similar Dutch basins using the groundwater model SIMGRO. The mitigation measures were modification of drainage and modification of urban water management. The two Dutch basins in this research were the Poelsbeek and Bolscherbeek, which are situated in a similar area as The Achterhoek. The three scenarios modelled in this study consist of raising the riverbed of watercourses, ranging from primary, to secondary, tertiary and ditches in varying magnitudes. Each scenario resulted in an increased groundwater level and therefore mitigating drought. However, as the ditches, tertiary, and secondary watercourses contributed to the waterflow of the larger streams it simultaneously resulted in an increase of dry spells for the Poelsbeek and the Bolscherbeek, because less water flows over the weirs.

Van den Eertwegh et al. (2021) analysed the impact of droughts on sandy soils in the south, midst and east of The Netherlands and the effectiveness of drought mitigation measures using the models SWAP and the 'Landelijk Hydrologisch Model' (National Hydrologic Model - LHM). Several drought mitigation measures were studied, including decreasing drainage by raising river beds and water levels of primary, secondary, and tertiary watercourses. Completely filling up the watercourses was not modelled in this study. Measures in the tertiary watercourses were found most effective in increasing the groundwater level, especially after a period of surplus in precipitation. However, due to the draining capacity of the primary and secondary watercourses the effect on the groundwater levels was largely dissipated in summer. However, the effect of the tertiary watercourses on the groundwater levels were underestimated in this model because of the large cell grid size (250 m x 250 m). Due to the large grid size the measures were applied to all watercourses in a model cell (primary, secondary, and tertiary) instead of solely the tertiary watercourses. Measures in the primary and secondary watercourses were found to increase the groundwater level all year round, but during winter resulted in situations with too high groundwater levels. This could be resolved by increasing the drainage capacity during winter, however this will also affect the groundwater level in summer.

While drought concerns increases, studies modelling the effectiveness of drought mitigation measures are minimal. The modeling studies of Querner and Van Lanen (2001) and Van den Eertwegh et al. (2021) contribute to the still little knowledge on the effect of reprofiling measures to reduce drainage. However, since there is a large variety in reprofiling measures that can contribute to reduced drainage, further research is necessary. Especially modelling studies with a smaller model grid size are beneficial to research the contribution and efficiency of reprofiling solely primary or secondary watercourses and the different magnitudes of reprofiling on groundwater levels. However, decreasing drainage is complex since going back to a state without drainage, as in history, is not feasible due to the agricultural and housing purposes of the land. Therefore, more research is necessary to find a balance in reprofiling the watercourses to decrease drainage without causing nuisance.

## 1.2 Research aim and questions

Given the lack of research on reprofiling measures to mitigate drought impacts, further research is necessary to prepare for future climate situations. Especially, in areas such as The Achterhoek drought mitigation measures are important for agriculture, nature and built environment. This research aims to provide insights on the effect of reprofiling watercourses on groundwater levels and storage. In order to define the effectiveness of reprofiling different dimensions of watercourses a comparison is made between primary and secondary watercourses, which is further explained in chapter 4.2.2. Additionally, reprofiling measures are studied for different magnitudes. Both choices, differentiating the type of watercourse and the different magnitudes of reprofiling, contribute to gaining a comprehensive view of the effect on groundwater levels and drought impact. Subsequently, the groundwater levels of each scenario are translated to groundwater characteristics, which are analysed and compared to define the effectiveness. The study area of this research is focused on one municipality in the Achterhoek, namely Winterswijk, in order to provide more detail of the reprofiling measures and to fit the available timeframe. In order to fulfil this aim, the following main research question is answered:

> *How does reprofiling watercourses influence groundwater levels and mitigate drought impacts in nature and agricultural areas?*

The main research question is answered by addressing the following sub-questions:

- *I. What is the individual effect of reprofiling primary and secondary watercourses on groundwater storage?*
- *II. What is the combined effect of reprofiling primary and secondary watercourses on groundwater storage?*
- *III. How does the effect on groundwater storage differ for agricultural and nature areas?*

## 1.3 Reading guide

Firstly Chapter 2, elaborates on the definition of drought, the factors influencing droughts and the different types of drought in order to better understand and apply drought mitigation measures. Chapter 3 provides basic understanding and implications of the groundwater model and characteristics used for this research. Chapter 4 describes the method used starting with the initial model set-up, followed by the model scenarios including reprofiling steps and lastly the data analysis. Chapter 5 presents the results while connecting it to the sub-questions. Chapter 6 discusses the results against the current body of literature, mentions the limitations of the study and suggests recommendations for further research. Lastly, Chapter 7 states the final conclusion of the research and answers the main research question.

# 2. CONCEPT OF DROUGHT

## 2.1 DEFINITION OF DROUGHT

Drought is an extreme climatic event over land, characterized by a precipitation deficit leading to a decrease in the natural water availability over a period of months to years (Spinoni et al., 2013; Dai, 2010; Mishra & Singh, 2010). Drought is recognized as a natural hazard, or environmental disaster, along with other hazards such as tropical cyclones, regional floods, earthquakes, and volcanos (Spinoni et al., 2013; Mishra & Singh, 2010; Bryant, 1991).

However, there are several factors differentiating droughts from other hazards. Firstly, there is no global understanding of what defines a drought, as this is strongly dependent on the situation or the function of a system. Additionally, in comparison to other hazards, the start and end of this climatic event is difficult to determine. Unlike a flood or storm, which have a sudden impact, droughts creep up slowly and show persistent consequences after its termination (Vogt & Somma, 2000; Spinoni et al., 2013; Mishra & Singh, 2010). Droughts should not be confused with aridity, because droughts are a temporary and recurring climatic event and aridity is a permanent climate feature of a certain region (Spinoni et al., 2013; Dai, 2010; Vogt & Somma, 2000). Nevertheless, arid regions are more susceptible to dry spells as the water system often relies on solely a few rainfall events (Dai, 2010). Additionally, the impacts of droughts are, in comparison to other natural hazards, non-structural and spread over large geo-graphical areas, which complicates the quantification of the impact and the assessment of mitigation measures (Wilhite, 2000). The last factor differentiating droughts from other hazards is the human factor impacting the occurrence of droughts. The growing population and economy put extra pressure on the already limited fresh water availability by excessive irrigation and over-exploitation of available water. Human activities such as over-farming, deforestation and urbanization contribute to the pressure on the fresh water availability as they increase erosion of the soil. Agricultural activities and deforestation for example, reduce root density and therefore destabilizes the soil. Urbanization increases water run-off which subsequently also increases erosion. Increased erosion of the soil leads to a decreased capability of the land to hold water (Mishra & Singh, 2010).

## 2.2 INTENSIFIED HYDROLOGICAL CYCLE

Droughts are also perceived as complex due to the large variety of parameters that contribute to this climatic event (Mishra et al., 2010). All these parameters are part of the global hydrological, which describes the flux and exchange of water between different global reservoirs as seen in Figure 2-1 (Marshall, 2013). Due to global warming a climate shift happens, where the probability of extreme hot weather will increase (Al-Ghussain, 2018). This results in greater evaporation and shorter but more intense precipitation events thus intensifying the hydrological cycle (Loáiciga et al., 1996; Mishra & Singh, 2010; Al-Ghussain, 2018). Increased temperature leads to increased evapotranspiration, simultaneously with no precipitation this leads to moisture depletion. Subsequently, moisture depletions reduces evapotranspiration, which decreases the relative atmospheric humidity. This results in longer periods before a saturated atmospheric state is reached and the saturated atmospheric state to hold more water. Lastly, this results in less but more extreme rainfall events (Mishra & Singh, 2010). All in all, this establishes a positive feedback loop increasing dry conditions (Mishra & Singh, 2010; Bravar & Kavvas, 1991). Studies of Lettenmaier et al. (1996), Aswathanarayana (2001), (cited from Mishra et al. (2010)), Caretta et al., 2022 confirmed that extreme weather events causing highly impactful droughts have become more likely and severe due to the anthropogenic climate change.

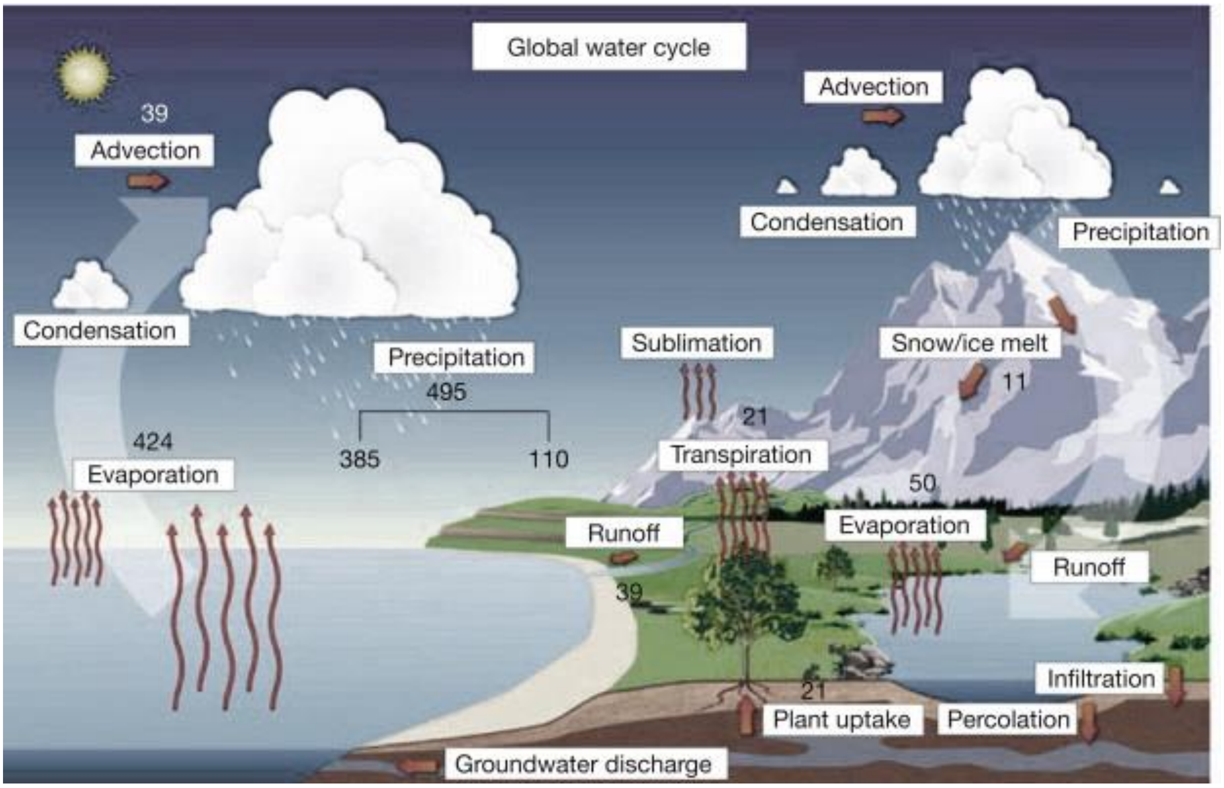


*Figure 2-1 The global hydrological cycle, with fluxes in $10^{12}$ $m^3yr^{-1}$ from Marshall (2013)*

## 2.3 Drought stages

In order to understand the concept of droughts, several stages of drought are classified. Firstly, the meteorological drought is defined as a precipitation deficit, more evapotranspiration than precipitation, in a region over a period of months to years (Dai, 2010). Meteorological droughts are amplified by local feedback of dry soils and high temperatures resulting in reduced relative atmospheric humidity and evaporation and possibly ignite other stages of drought (Pezij, 2019; Dai, 2010). Secondly, follows the agricultural droughts, which is defined as crop failure and reduced plant growth as a consequence of a precipitation deficit (Dai, 2010). Agricultural droughts are often reliant on the soil moisture of a region. The agricultural drought is followed by the hydrological droughts which is a depletion of surface- and groundwater and happens more slowly (Dai, 2010). Then the socio-economic drought is felt when there is a decreased availability of water for industries or drinking water extractions. Lastly, Mishra and Singh (2010) discussed a new type of drought: groundwater drought. Groundwater drought is the last stage commonly defined by the decrease in groundwater level. Drought slowly propagates through these stages, while the effect decreases but spreads over a longer time period on each terrestrial part. Additionally, The slow propagation of drought through each system amplifies the unexpected behaviour of drought.

# 3. Model theory

This chapter elaborates on the concepts behind the groundwater model. Firstly, the concept of the groundwater model and the underlying equations are elaborated. Followed by the model packages used and assumptions made in Amigo. Lastly, the groundwater characteristics used to analyse the groundwater output are elaborated.

## 3.1 Groundwater modelling

While groundwater models are merely a simplification of reality, they are often found useful to simulate the groundwater system and to address groundwater problems and support the decision making process (Kumar, 2019). There are many different groundwater models available, each with their own capabilities and limitations. For this study the groundwater model Amigo, provided by the regional water authority of this research area, is used to simulate the effectiveness of reprofiling measures on groundwater levels. Amigo (Actueel Modelinstrumentarium Gelderland Oost)[2] (De Weme et al., 2019) operates with iMOD (Vermeulen & Roelofsen, 2023), which is an interactive modelling software based on the groundwater modelling code iMODFLOW[3] (Harbaugh, 2005) and the unsaturated zone modelling code MetaSWAP (Van Walsum & Groenendijk, 2008). As the focus of this study is on groundwater, MetaSWAP is not further elaborated.

### 3.1.1 iMODFLOW

iMODFLOW executes the groundwater flow equations with the finite difference method (Hendriks, 2010). The groundwater flow equations are based on Darcy's law and the continuity principle (Hendriks, 2010). The three dimensional groundwater flow with a constant density through a porous medium is described by the following partial-differential equation (Harbaugh, 2005):

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)+W=S_s\frac{\partial h}{\partial t}\ [1]$$

Where $K_{xx}/k_{yy}/k_{zz}$ are the hydraulic conductivities along the x, y, and z coordinate [L/T], h is the potentiometric head [L], W is the volumetric flux per unit volume representing sources and/or sinks of water [$T^{-1}$], $S_s$ is the specific storage of the porous material [$L^{-1}$] and t is a period of time [T]. This equation holds for groundwater flow under nonequilibrium conditions in a heterogeneous and anisotropic medium (Harbaugh, 2005). In all equations mentioned in this chapter the unit L stands for any unit of length and the unit T stands for any unit of time. The groundwater flow equation in finite-difference form follows from the application of the continuity equation. The continuity principle, also referred to as the water balance, is a simple approximation of hydrological processes. The continuity principle defines that the sum of flow in and out a cell is equal to the change in storage. From the continuity principle follows the balance of flow for a cell, described as (Harbaugh, 2005):

$$\Sigma Q = SS\frac{\Delta h}{\Delta t}\Delta V\ [2]$$

In which Q is the flow rate into the cell [$L^3T^{-1}$], SS is the specific storage [$L^{-1}$], $\Delta$ V is the volume of the cell [$L^3$], and $\Delta$ h is the change in head over a certain time interval $\Delta$ t [T]. Equation 2 is rewritten to the exact one-dimensional steady state flow through a block of aquifer extending from one node to an adjacent node using Darcy's law (Harbaugh, 2005):

[2] English: Actual Model Instrument Gelderland East

[3] MODFLOW 2005

$$Q = K_s A \frac{\Delta h}{L} \; [3]$$

In which $K_s$ is the saturated hydraulic conductivity [L/T], A is the cross-sectional area through which the water flows [$L^2$], and $\Delta h/L$ is the hydraulic gradient [-]. Darcy's law for a three dimensional model grid is illustrated in Figure 3-2, representing the difference in volume flux being dependent on the hydraulic head entering and exiting the cell and the volume of the cell.

The finite difference method is a numerical method that divides the groundwater flow domain of interest into a grid of rectangular cells. Centred in each cell is a node that contains the information of that particular cell. For each node the value of the hydraulic gradient or a boundary condition is specified. The finite difference method relates each node in a grid to the hydraulic head of its neighbouring nodes and in transient calculations to the hydraulic head at the node of a previous time step (Hendriks, 2010). When a value of a node is unknown it can be calculated based on considerations of the flow patterns around the node (Shaw et al., 2017).

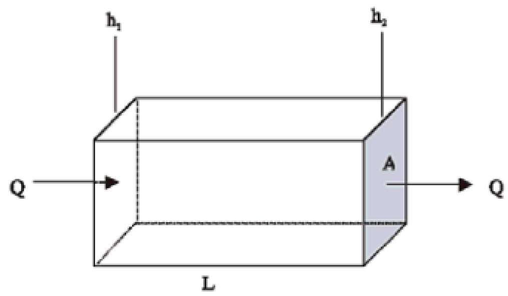

*Figure 3-1 Illustration of Darcy's law, (Harbaugh, 2005)*

Additionally, iMODFLOW assumes quasi 3D flow, which represents the horizontal flow in the model layers and vertical flow simply being represented by vertical conductance between the layers (Harbaugh, 2005). The assumption of quasi-3D flow holds if the vertical transmissivity of the separating layers is very small compared to the horizontal transmissivity of the aquifer (Vermeulen, 2006).

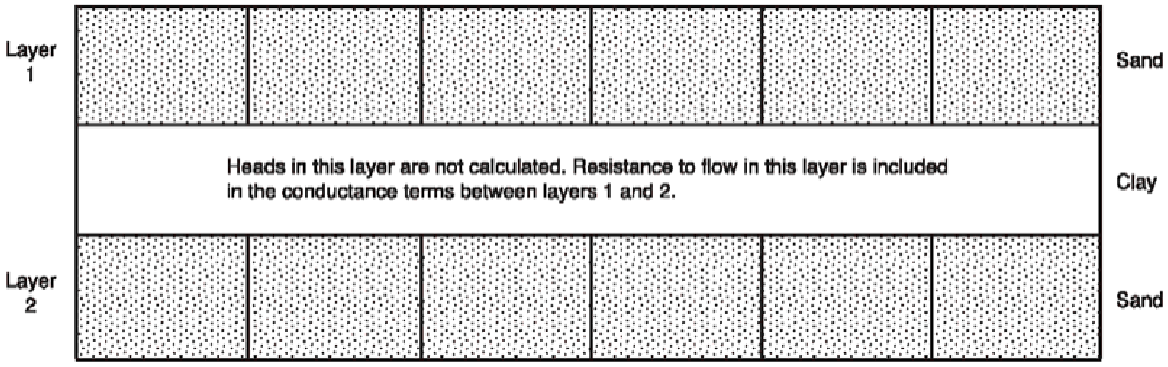


*Figure 3-2 Cross-section of quasi 3D flow in which vertical flow is represented by a conductance term (From McDonald and Harbaugh, 1988)*

### 3.1.2 Model packages

iMOD operates based on a variety of packages representing different aspects contributing to the functioning of the groundwater model. The packages applied in Amigo and relevant for this research are further elaborated.

The boundary package defines which cells are contributing to the flow, which cells are inactive and which cells contain a fixated head (Vermeulen & Roelofsen, 2023). The cells with a fixated head require monthly input and define the boundaries of the research area. The starting package defines the initial starting head of the model simulation for the whole research area (Vermeulen & Roelofsen, 2023). The river package defines the watercourses in the model and requires as input the location, the water level

[L], the bottom level [L], the conductance [$L^2/T$] and the infiltration factor [-] of the rivers, respectively watercourses. The river package simulates a permanent presence of water in the watercourses from which water infiltrates in the soil or to which water discharges to the watercourse (Vermeulen & Roelofsen, 2023). The parameters from the river package find their origin in the segment package. The segment package represents the water level [L], bottom heights [L], infiltration factor [-] and river resistance [-] of the riverbed, as seen in Figure 3-3. The shape of the watercourse is assumed rectangular for this research but can be varied. Figure 3-3 shows an increased groundwater table in comparison to the water level in the watercourse, thereby representing a draining watercourse as the groundwater will flow from the soil to the watercourse.

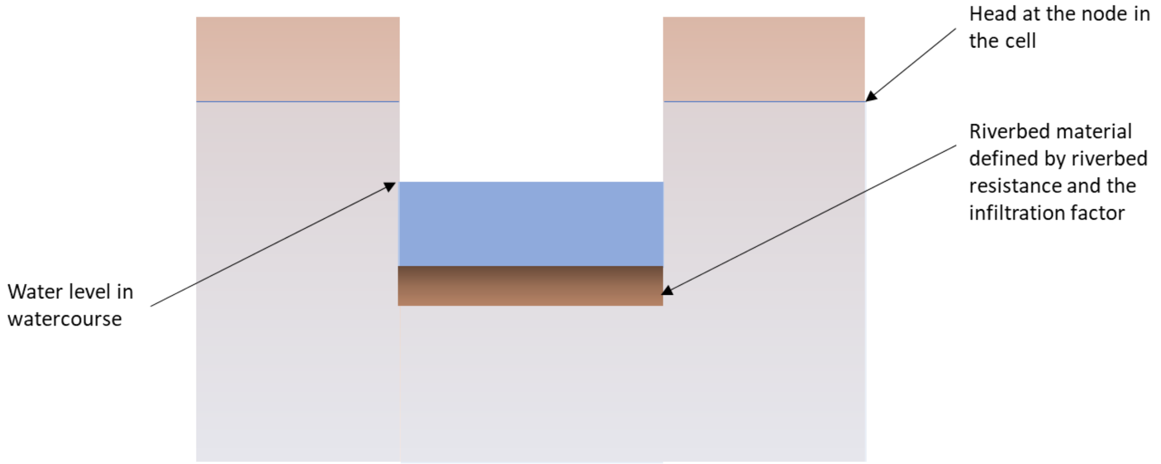


*Figure 3-3 Representation of a watercourse cross-section in a model cell in the segment package*

The information from the segment package is gridded by iMOD per river segment. The information of the model cells in such a segment are interpolated in order to define one value for each segment (Vermeulen & Roelofsen, 2023). The conductance is defined based on the wetted perimeter *wp* [L], the length of the segment *L* [L], the resistance of the riverbed *c* [L] and optionally the infiltration factor *f* [-]. The wetted perimeter is calculated based on the interpolated water level [L] and bottom height [L] at each location along the segment (Vermeulen & Roelofsen, 2023). The infiltration factor is optional and corrects the conductance iteratively whenever the stage is higher than the computed groundwater level (Vermeulen & Roelofsen, 2023). The conductance is described as:

$$Conductance = \frac{wp * L}{c} * (f) \ [3]$$

The overland flow package defines the elevation above which outflow of groundwater will occur when exceeded by the groundwater head. Once the overland flow package is activated the water won't return as groundwater and is discharged out of the model (Vermeulen & Roelofsen, 2023). There is no routing package activated in Amigo, therefore no routing between the surface water segments is possible (Vermeulen & Roelofsen, 2023), (De Weme et al., 2019).

### 3.1.3. Amigo

The infiltration factor in Amigo has been set on 0 for the whole area except for the Boven Slinge and a part of the Groenlose Slinge, which were assigned an infiltration factor of 0.3 (De Weme et al., 2019). Amigo translated the hydrogeological soil components from 19 layers to 15 layers from REGIS II[4] to

[4] REGIS II version 2.2 is a hydrogeological model of the subsurface up to 500 meter below NAP (*REGIS II, Hydrogeologisch Model (HGM)*, n.d.)

reduce running times. Therefore a few soil layers are either merged together or are incorporated in other soil layers (De Weme et al., 2019).

## 3.2 Groundwater characteristics

The groundwater model as described simulates output in the form of groundwater heads over the model period of 2010-2020 of which the first two years are necessary to provide accurate values. In order to evaluate such large data sets, average values such as the groundwater characteristics are used to analyse the effectiveness of the measures. These groundwater characteristics are often used in The Netherlands to describe the dynamics of the groundwater system and are defined as follows for this research:

**HG3 - highest groundwater level:** the highest groundwater heads during one hydrological year, from the 1st of April until the 31st of March, with measuring data twice per month.

**LG3 - lowest groundwater level**: the lowest groundwater heads during one hydrological year, from the 1st of April until the 31st of March, with measuring data twice per month.

**VG3 - spring groundwater level**: the average groundwater head on the 14th of March, 28th of March and the 14th of April for a hydrological year.

**XG3**: represents the HG3, LG3 and VG3.

**GHG - average highest groundwater level:** the average of HG3 over a consecutive period of at least 8 years.

**GLG - average lowest groundwater level:** the average of LG3 over a consecutive period of at least 8 years.

**GVG - average spring groundwater level**: the average of VG3 over a consecutive period of at least 8 years.

**GG - the average groundwater level:** the average groundwater levels over a consecutive period of 8 years.

**GXG**: represents the GHG, GLG, GVG, and GG.

Several studies have used these definitions for their research such as: De Gruijter et al. (2004); Van Kekem et al. (2005); Finke et al. (2002); Knotters and Bierkens (1999) and Bierkens (1995). The studies of Bierkens (1995), De Gruijter et al. (2004) and Knotters and Bierkens (1999) confirm that a period of 8 years is sufficient in order to define the dynamics response of the groundwater system in relation to precipitation, which corresponds to the modelling period of 2012-2020 for this study. According to Knotters and Bierkens (1999) some systems had a response time of less than year, but it is necessary to at least have one year of data in order to gain information on both low and high groundwater levels. Every year can differ resulting in three dry years to be followed by a wetter year and therefore a time period of 8 consecutive years is often found acceptable to define the groundwater dynamics.

# 4. METHOD

This chapter firstly gives a description of relevant aspects of the research area with regards to the water system, followed by a step by step elaboration of the initial model set-up and how reprofiling of the watercourses was translated into the groundwater model. Lastly, the analyses of the output groundwater heads are discussed while connecting this to the sub-questions.

## 4.1 SITE DESCRIPTION WINTERSWIJK

Around 1000 years B.C., The Achterhoek was characterized mainly by wetlands with a few streams and ridges locally draining the area. However, extensive drainage networks were formed in order to drain the land for better crop yield of the agricultural lands (Zuidhoff & Van Beek, 1998). Only currently the extensive drainage networks are resulting in drought problems. Multiple parties, such as regional water authorities, provinces, nature organizations, and drinking water companies are participating in increasing the groundwater storage in The Achterhoek. The Achterhoek has been experiencing a lot of drought issues because of the limited water inflow, the elevation of the land and soil composition (*Droogte in De Achterhoek*, n.d.), (Wesselink, 2022). The research area of this study, Winterswijk, is also located in The Achterhoek. The area of Winterswijk is heavily dependent on fresh water availability as roughly 75% of the area consists of agricultural land and another 14% consists of nature areas (CBS Statline, n.d.).While fresh water is of importance for Winterswijk, the area has limited inflow coming from two stream basins and the strong elevation of the area contributes to the quick throughflow of water, as shown in Figure 4-1. The research area of this study consist of the two stream basins in Winterswijk.

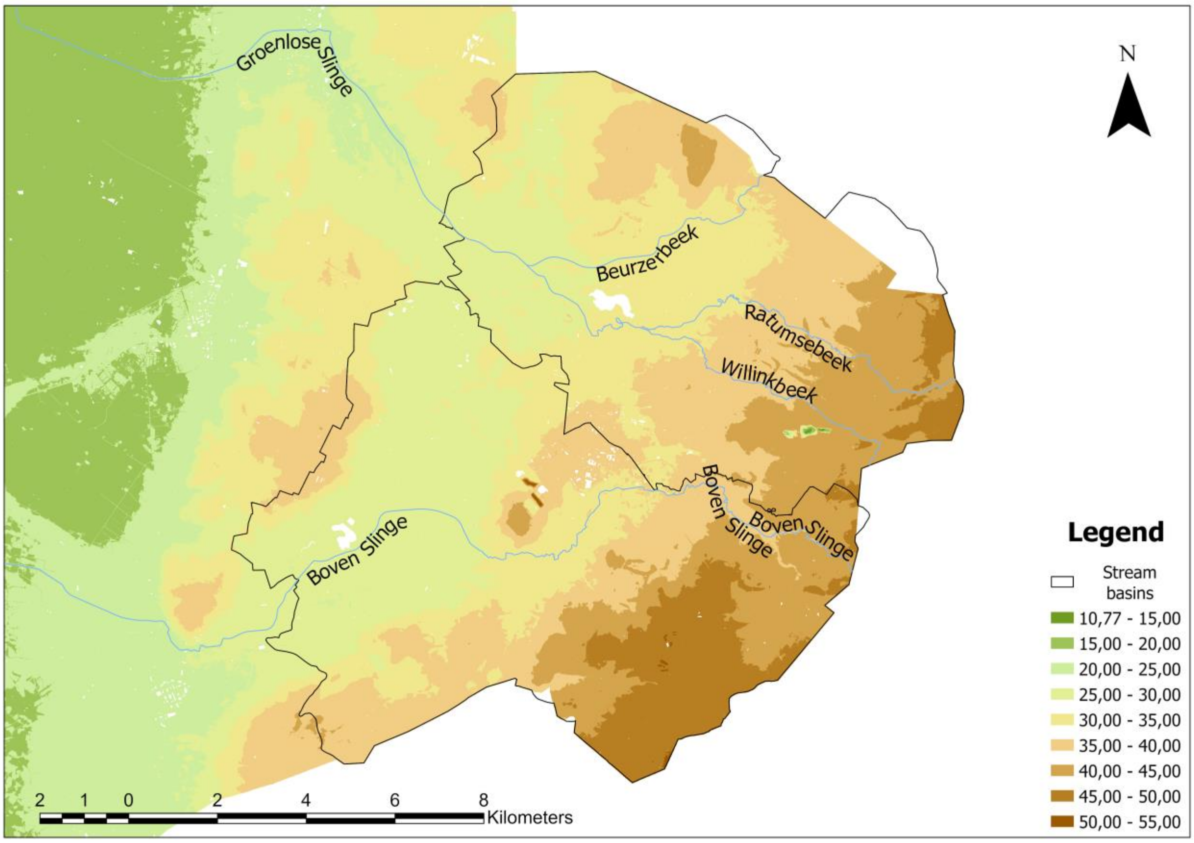


*Figure 4-1 Elevation of the municipality of Winterswijk and surrounding municipalities*

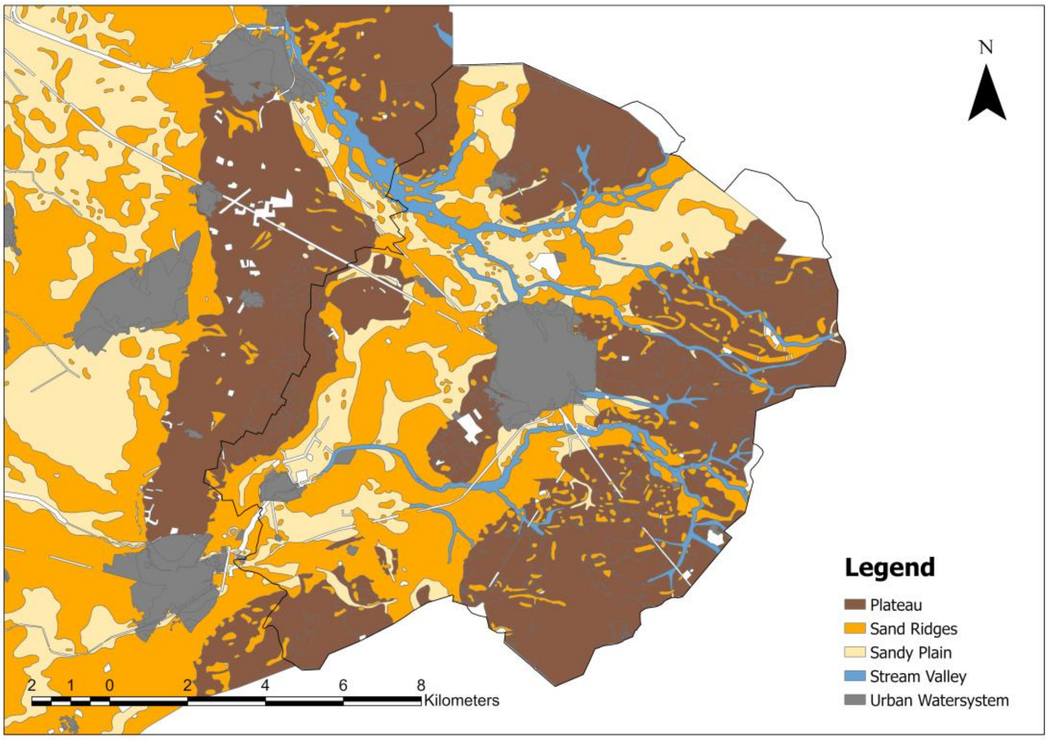


*Figure 4-2 Water systems in Winterswijk (H+N+S Landschapsarchitecten, 12-01-2023)*

Geomorphological research for the regional water authority characterized the following water systems in Winterswijk Figure 4-2. The plateau is a shallow, strongly elevated water system consisting of mainly sand resulting in little water inflow, little storage capacity and significant infiltration capacity. The sandy plain is also a shallow water system consisting of sand but in comparison to the plateau, this is a flat lying area. The sandy plain has little storage capacity but significant infiltration capacity. The sand ridges are a deep water system with significant storage capacity and a few watercourses present. The sand ridges originates from historic meltwater gullies, that had cut deep in the soil and were filled with sand, sand and clay and then sand again (Van den Bosch & Kleijer, 2003), (De Weme et al., 2019). The stream valley has little storage and infiltration capacity and predominantly consists of watercourses. Lastly, the urban water system consist of a lot of paved area which results in little infiltration while additionally the storage capacity can vary. The soil composition of this area shows a high level of heterogeneity as the difference between the plateau and sand ridges are shown in Figure 4-3.

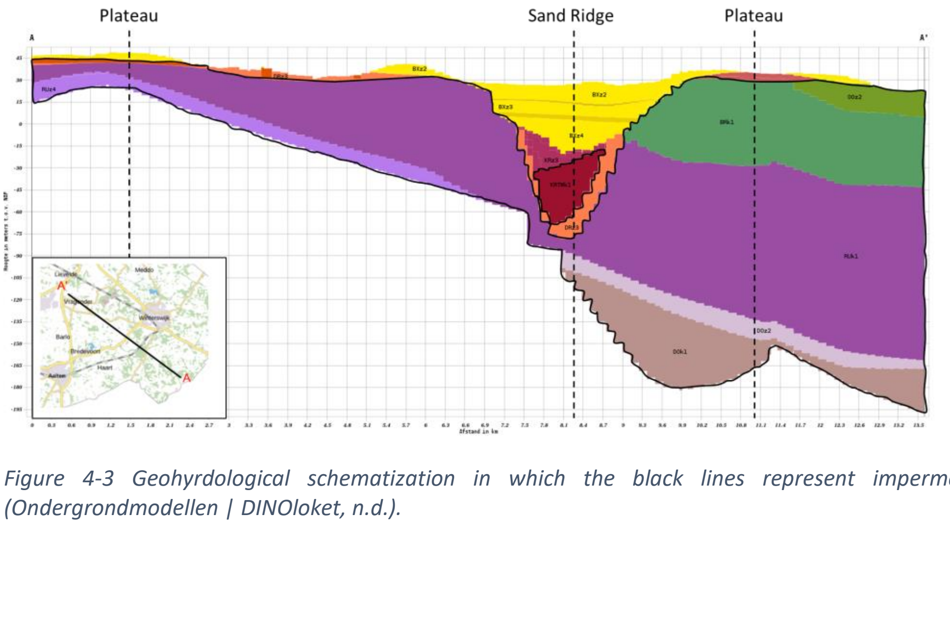


*Figure 4-3 Geohyrdological schematization in which the black lines represent impermeable layers (REGIS 2.2) (Ondergrondmodellen | DINOloket, n.d.).*

## 4.2 Data collection

Amigo version 3.0 is calibrated and validated by the engineering company Arcadis and for further elaboration is referred to De Weme et al. (2019). The groundwater model is run for the period of 2010-2020. The first two years are necessary for the model to produce reliable results and therefore are not used in the analysis. A buffer zone of 3 km is added to the research area to account for the interaction with the surrounding water system.

### 4.2.1 Initial model set-up

The groundwater model Amigo operates as follows. For the groundwater model to be run at a cell grid size of 25 meter, hereafter referred to as the 25 meter model, input is required from running the model at a cell grid size of 250 meter, hereafter referred to as the 25 meter model. The 25 meter model requires starting and constant head input from the 250 meter model. In order to model 1 scenario, first a 250 meter model is run and then the output of this model is used as input for the 25 meter model. However, to reduce model run times an analysis has been performed on the difference between using the output of a reference 250 meter and a scenario 250 meter as input for the scenario 25 meter model. The scenario used for this analysis consists of a set of extreme measures from the project of Witteveen+Bos has been used, consisting of raising the riverbed with 50 cm and raising the bed of the main streams with 70 cm. The analysis of the reference 250 meter model has been performed for the constant head, starting head and the research area as seen in Figure 4-4.

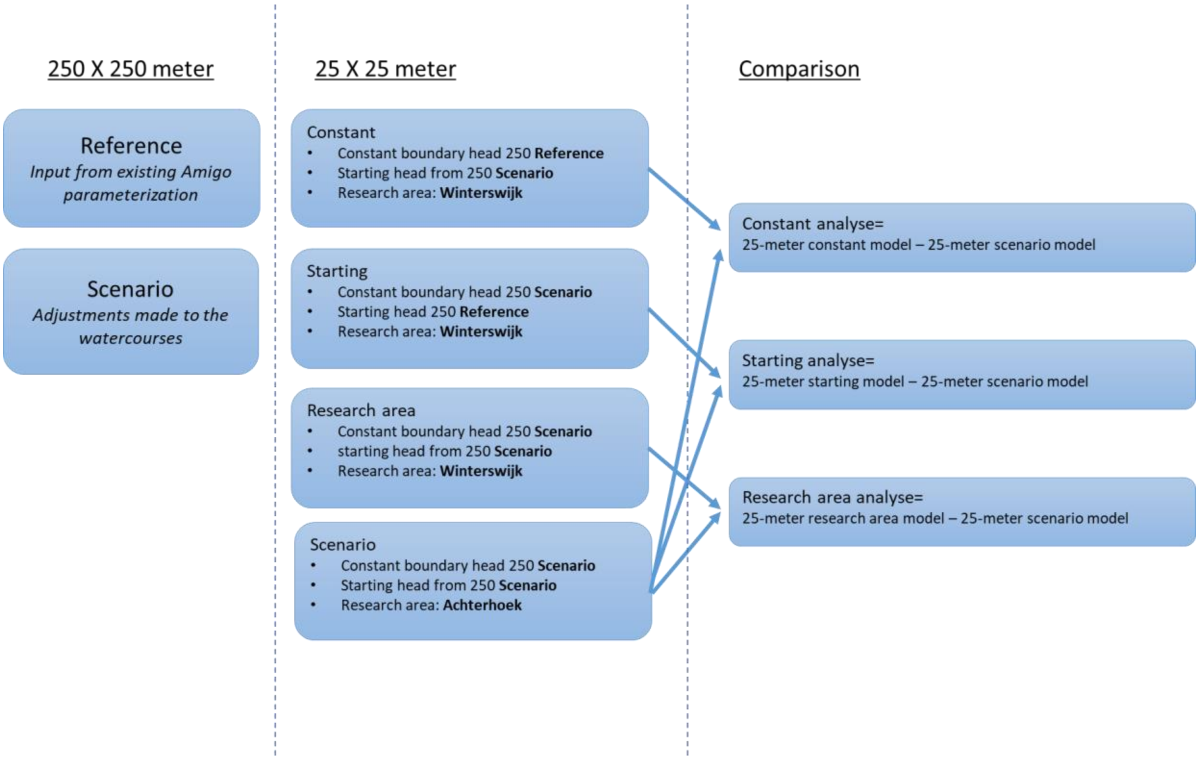


*Figure 4-4 Flow diagram method for analysis of the 250 meter model*

#### *4.2.1.1 Constant head analysis*

The constant boundary heads provide monthly input for the head at boundary of the research area. The constant analysis gave the following differences after an initialisation period of 2 years, Figure 4-5. As can be seen the difference between input from the 250 Scenario and 250 Reference model are little and only visible in the buffer zone.

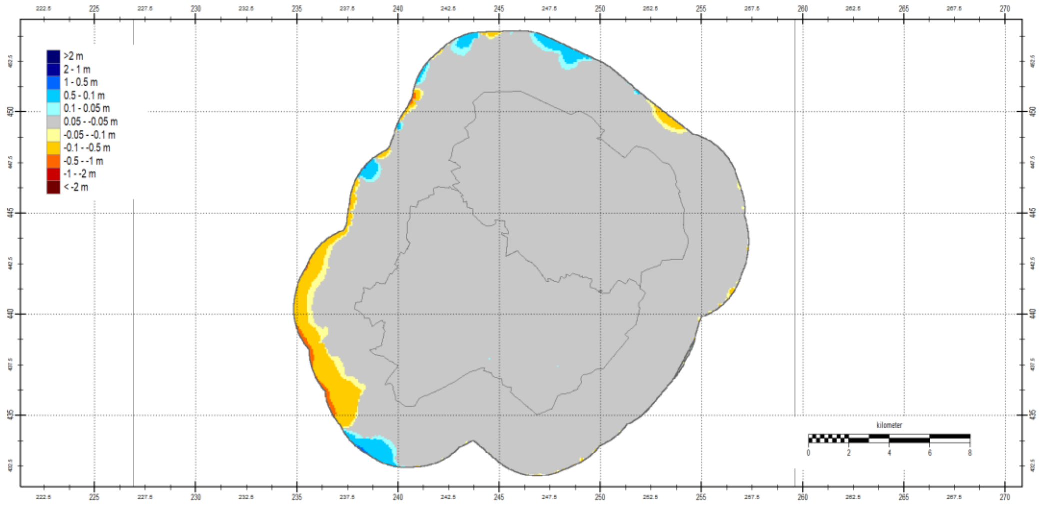

*Figure 4-5 Difference constant head 2014-04-14*

#### *4.2.1.2 Starting head analysis*

The starting heads input for the 25 meter model are the groundwater heads output from a wet year of the 250 meter model, because it is easier for the model to lower the groundwater heads to an average situation than it is to heighten the groundwater heads. For the groundwater heads to heighten, the model is dependent on a significant precipitation event while lowering the groundwater heads happens due to gravitational drainage. Therefore, for this research the date of the starting heads input is 2013-01-01, as the year of 2012 showed above average precipitation with regards to the long term average (KNMI - Jaar 2012, n.d.). The starting analysis showed a visible difference inside the research area after an initialisation period of 2 years, Figure 4-6. While the difference is not extremely large, between the -0.1 and -0.5 meter, it is too much to use this confidently for modelling.

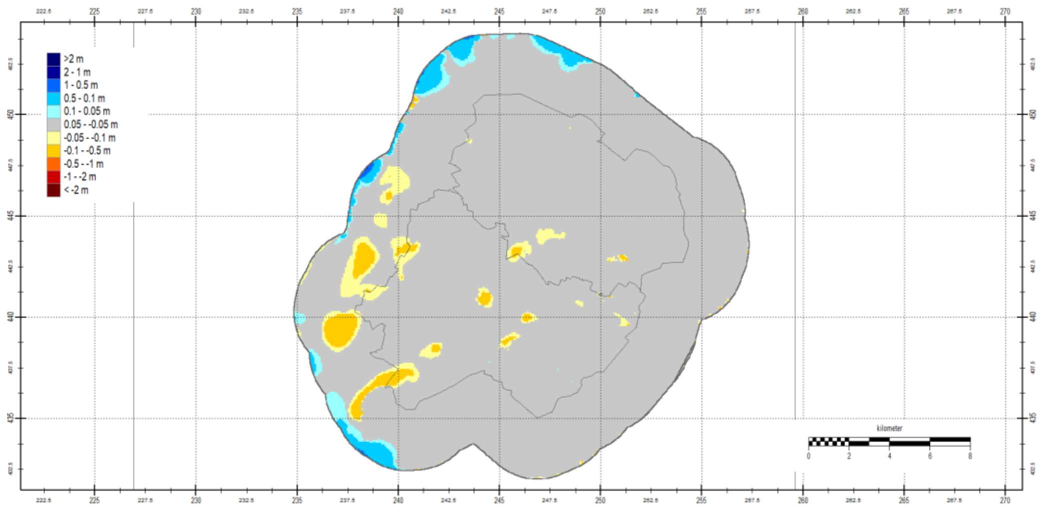

*Figure 4-6 Difference starting head 2014-04-14*

Another analysis was done with the starting heads of the reference 250 model increased with 0.5 meters, which showed little difference, Figure 4-7.

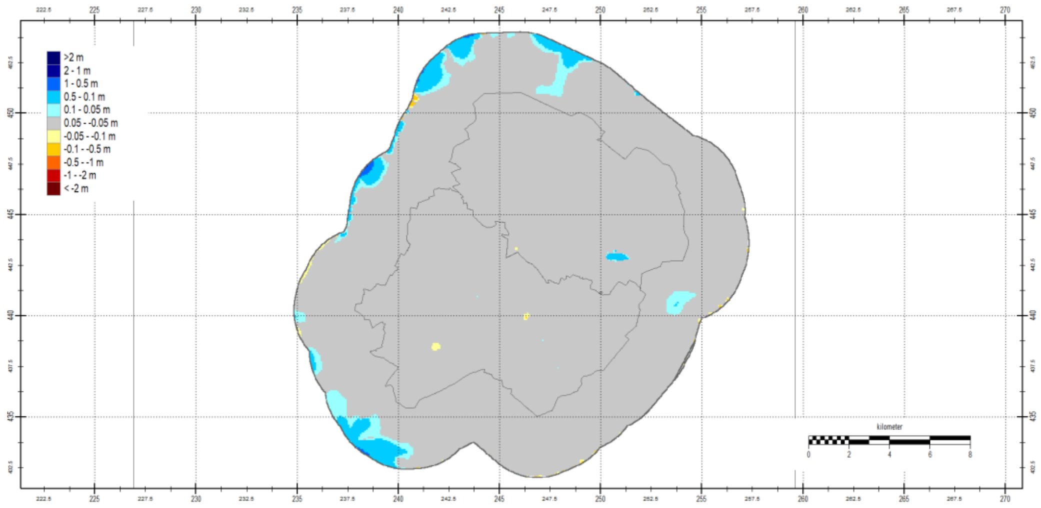


*Figure 4-7 Difference starting head +0.5m 2014-04-14*

#### *4.2.1.3 Research area analysis*

Lastly, an analysis has been done on the effect of different research areas on the groundwater heads. This is because the scenario 25 meter model runs with a different research area than the reference 25 meter model. Figure 4-8 shows the little influence of a differing research area for the model output.

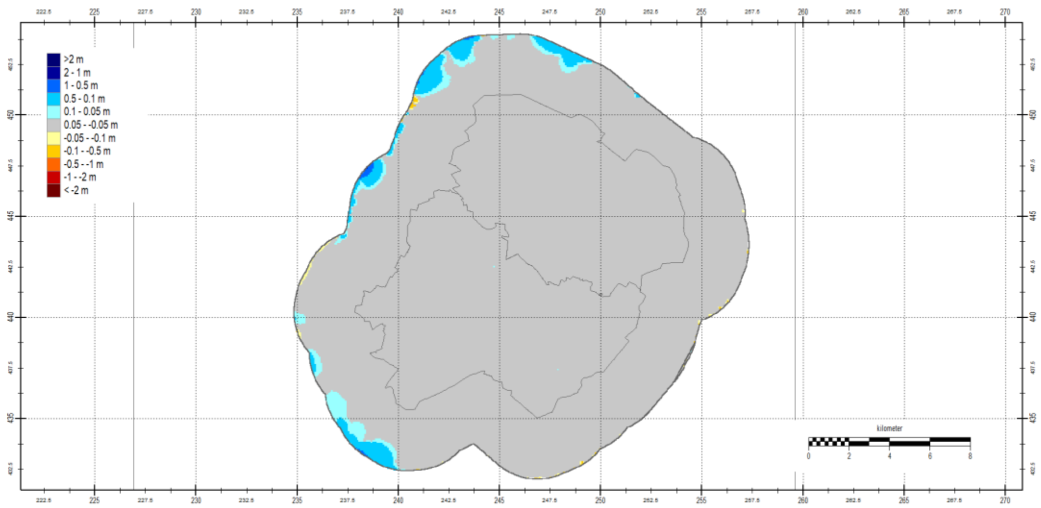


*Figure 4-8 Difference research area 2014-04-14*

All in all, these analysis have shown that using the 250 reference model output as input for the starting (+0.5 m) and constant boundary head of the 25 scenario models would lead to little difference and therefore the reference 250 meter model will be used as input for the 25 meter models in this study.

### 4.2.2 Reprofiling of watercourses

Reprofiling watercourses is a very broad definition and can encompass a variety of measures to the watercourse. In this research reprofiling of watercourses will solely consist of raising the riverbed of the watercourse while simultaneously raising the water level, in such a manner that the volume of water in the watercourse remains the same. Raising the riverbed and level will be done with steps of

25%, 50%, 75% and 100%. To prevent a water level above surface level, raising the bed will be done over the distance between the water level and the surface level, as can be seen in Figure 4-9.

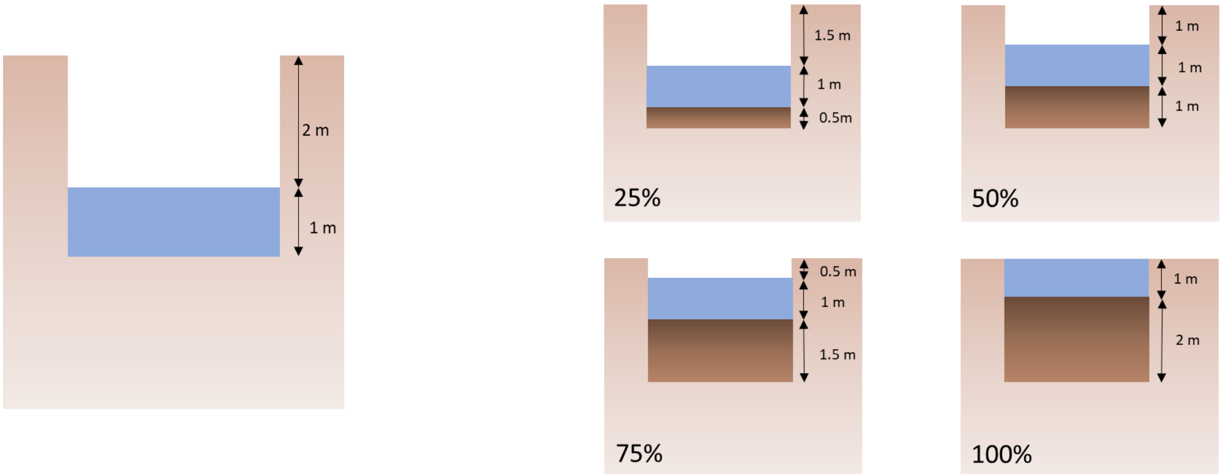


*Figure 4-9 Representation of reprofiling watercourses with steps of 25%, 50%, 75% and 100% for this research*

The reasoning behind these reprofiling choices is related to the river package as described in the Theory. The river package input conductance is based on the wetted perimeter *wp* [L], the length of the segment *L* [L], the resistance of the riverbed *c* [L] and optionally the infiltration factor *f* [-] as described in equation 3.By raising the riverbed and level, the wetted perimeter remains the same and therefore the conductance can also remain the same. In contrary to adjusting the water level, this would also mean adjusting the wetted perimeter and conductance of the watercourses. Adjusting these parameters would be done in the segment package and are based on interpolation of the river segments. Additionally, in the segment package the watercourse is not schematized as a rectangle but a trapezium. Due to these factors, it was not possible to reproduce the same values as the original conductance values. Therefore, the choice was made to remain the approximate same wetted perimeter by remaining the same water volume in the watercourses and thereby reducing the amount of uncertainty in changes to the groundwater model. Additionally, the choice was made to raise both the riverbed and level in the watercourses in contrary to solely the riverbed as this is assumed to have more significant impact on the groundwater levels.

#### *4.2.2.1 Scenario modelling*

For the scenarios a division in reprofiling has been made between primary and secondary water courses. Figure 4-10 shows the primary watercourses in dark blue and the secondary watercourses in light blue. The effectiveness of the water courses individually and together will be modelled in order to define the effect of the scenarios. The following scenarios will be modelled:

<u>Reprofiling primary watercourses</u>

Reprofiling of the primary watercourses will be done in steps of 25%, 50%, 75% and 100%. The primary watercourses are defined in the model as ‘Legger watergangen’ which are watercourses that are documented in the Legger. This means that these water courses fall under jurisdiction of the regional water authority and a set of rules from the Keur are applicable to these watercourses (*De Regels Van Het Waterschap*, n.d.). The Keur encompasses rules about, for example, preventing damage to the dikes, maintenance of the watercourses and preventing water shortage (Rivierenland, 2022). The primary watercourses are based on an actual SOBEK-model (2014) and the water levels in the watercourses vary for summer and winter (De Weme et al., 2019).

Reprofiling secondary watercourses

Reprofiling the secondary watercourses will also be done in steps of 25%, 50%, 75% and 100%. The secondary watercourses are often privately owned and typically smaller than primary watercourses. The secondary watercourses are derived from the TOP-10 lines and are categorizes as small, normal and wide. The water level is derived from the surface level (AHN2) and no distinction has been made between summer and winter (De Weme et al., 2019).

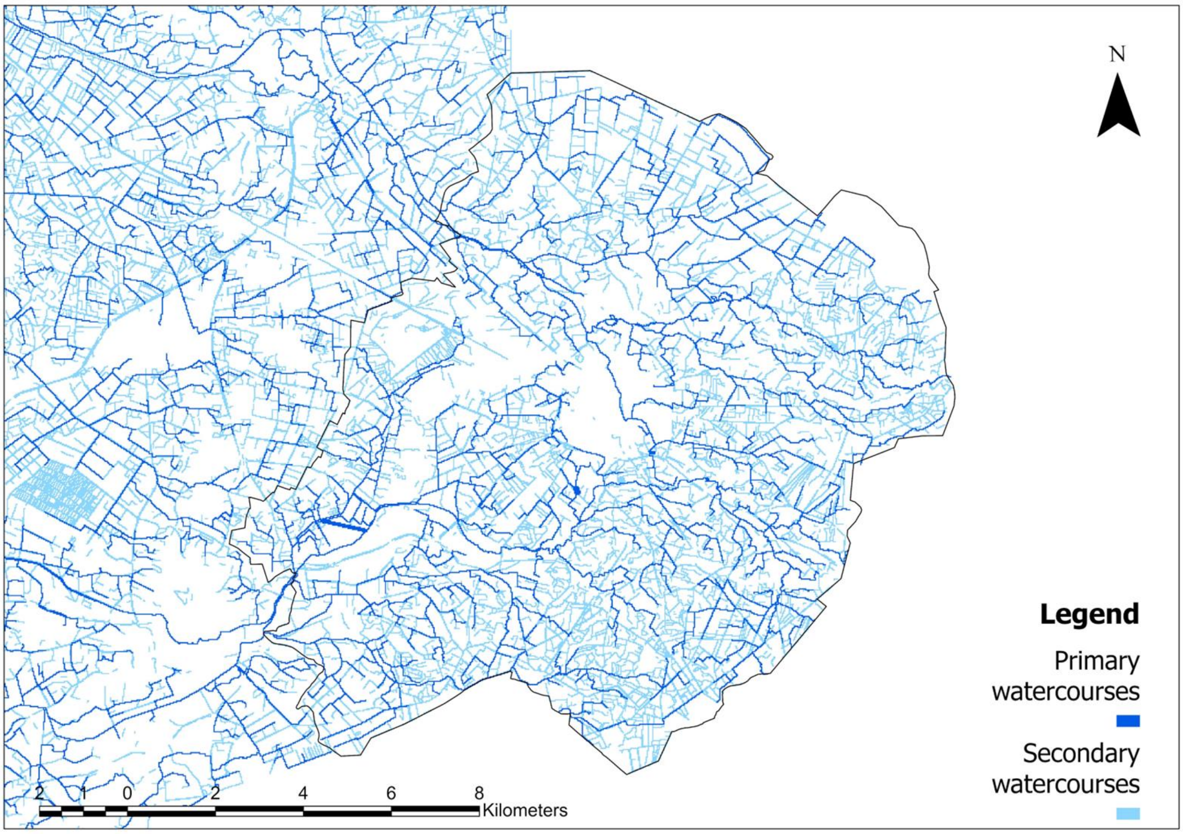


*Figure 4-10 Primary and secondary watercourses in Winterswijk*

Reprofiling both the primary and secondary watercourses

In this scenario the primary and secondary watercourses are raised simultaneously. This scenario will follow the same steps of 25%, 50%, 75% and 100% for simultaneously increasing the height of both the primary and secondary watercourses.

## 4.3 Data analysis

The effectiveness of reprofiling primary and/or secondary watercourses is analysed with groundwater characteristics that represent groundwater droughts. Therefore, solely the following groundwater characteristics will be used for analysis: GLG, GG, GVG, LG3. Other groundwater characteristics, such as GHG and HG3, which describe wet conditions, will not be further elaborated in the results but will be used in the discussion to place the effects in perspective.

### 4.3.1 Spatial analysis

The spatial analysis provides insights in the spatial distribution of the effect of reprofiling the primary and/or secondary watercourses. For the spatial analysis the effect of each reprofiling measure has been plotted over the research area Winterswijk. Firstly, the GLG, GG and GVG were analysed per scenario. The GLG is an average of the three lowest groundwater levels per year over an average of eight consecutive years. Therefore, the increase in GLG gives an indication of how effective the reprofiling measures are to alleviate droughts in long-term perspective. The GG is the average of groundwater levels over eight consecutive years. The increase in GG gives an indication on how the reprofiling measures impact the average situation of groundwater levels in Winterswijk. Therefore, the increase in GG provides nuance to the extreme values. The GVG is the average of spring groundwater levels per year over an average of eight consecutive years. The GVG are measured at the start of the hydrological year and crop growing season. The increase in GVG therefore indicates the increase in groundwater levels or storage the hydrological year starts with. Nevertheless, this does not always corresponds to a lasting increase in groundwater levels. All groundwater characteristics are an average over the modelling period 2012-2020.

Secondly, the spatial distribution of the LG3 for one wet and one dry year will be visualized over the area of Winterswijk. The LG3 give an indication of the most extreme situations with regards to groundwater levels that can occur. Therefore, the increase of the LG3 provide information on whether the reprofiling measures can alleviate these extreme situations. The spatial distribution will be visualized for both a dry and a wet year in order to compare the effect on both situations. For this study the dry year will be the hydrological year 2018 (04-2018/03-2019) and the wet year will be the hydrological year 2017 (04-2017/03-2018) (KNMI - Jaar 2017, n.d.), (KNMI - Jaar 2018, n.d.).

During a previous project of Witteveen+Bos the groundwater head outputs at the transition between the plateau and the descending slope were found to be unreliable. In Amigo a constant value has been set for the transmissivity of the aquifers. In actual situations the saturated zone decreases which reduces the transmissivity and groundwater flow to these lower lying areas. However, Amigo does not accurately represents these declining transmissivity which results in a sudden drop in groundwater levels (Benninga & Versteegen, 2023). The areas which are selected as unreliable have a difference in GVG between the reference model run and the groundwater model BRO[5] of more than 1 meter and are indicated in Figure 4-11 (Benninga & Versteegen, 2023).

[5] Programma Basisregistratie Ondergrond, 2022. Model Grondwaterspiegeldiepte. English: National Key Registry of the Subsurface, 2022. Water table depth model.

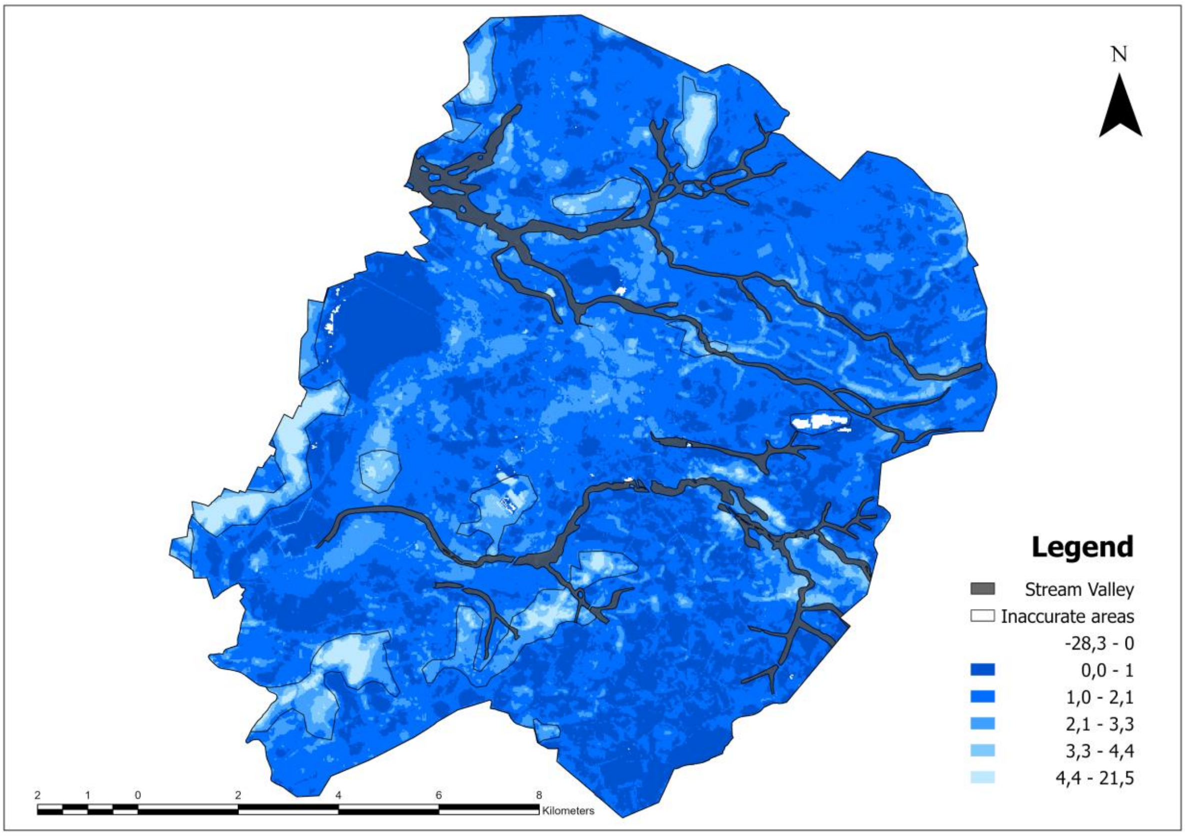


*Figure 4-11 The GG of the reference scenario with regards to the surface level [m]*

Additionally, the mean groundwater characteristics and storage were calculated for the area of Winterswijk. The mean groundwater characteristics provide information on the absolute differences between the effect of each reprofiling step and of the difference between the groundwater characteristics. The mean groundwater storage is calculated based on the storage coefficient of the area. The storage coefficient is obtained from a project of Witteveen+Bos in this area. The storage coefficient is based on output from Amigo/MetaSWAP. The storage coefficient is calculated as an average of the values between half of march and half of April over the model period 2012-2020. Additionally, the storage coefficient is maximized in the urban area t0 0.2. The mean groundwater storage gives an indication of the absolute values of water added in mm in the soil due to the reprofiling measures. The mean groundwater storage can be linked to the mean precipitation deficit from the KNMI climate scenarios because the precipitation deficit depicts the amount of extra groundwater storage is necessary in the area to prevent drought issues in the soil.

### 4.3.2 Time series analysis

The time series analysis provides insights in the effect of the reprofiling measures on the groundwater levels throughout time. The time series analysis is solely applicable to a specific point in the research area, the sample points. The sample points in this research area are chosen based on the water systems as shown in Figure 4-2. Each water system has one representative sample point. The sample points serve to show how different systems respond to the reprofiling measures. However, due to the small sample size, the sample points do not accurately represent the water system. The sample points are shown in Figure 4-12.

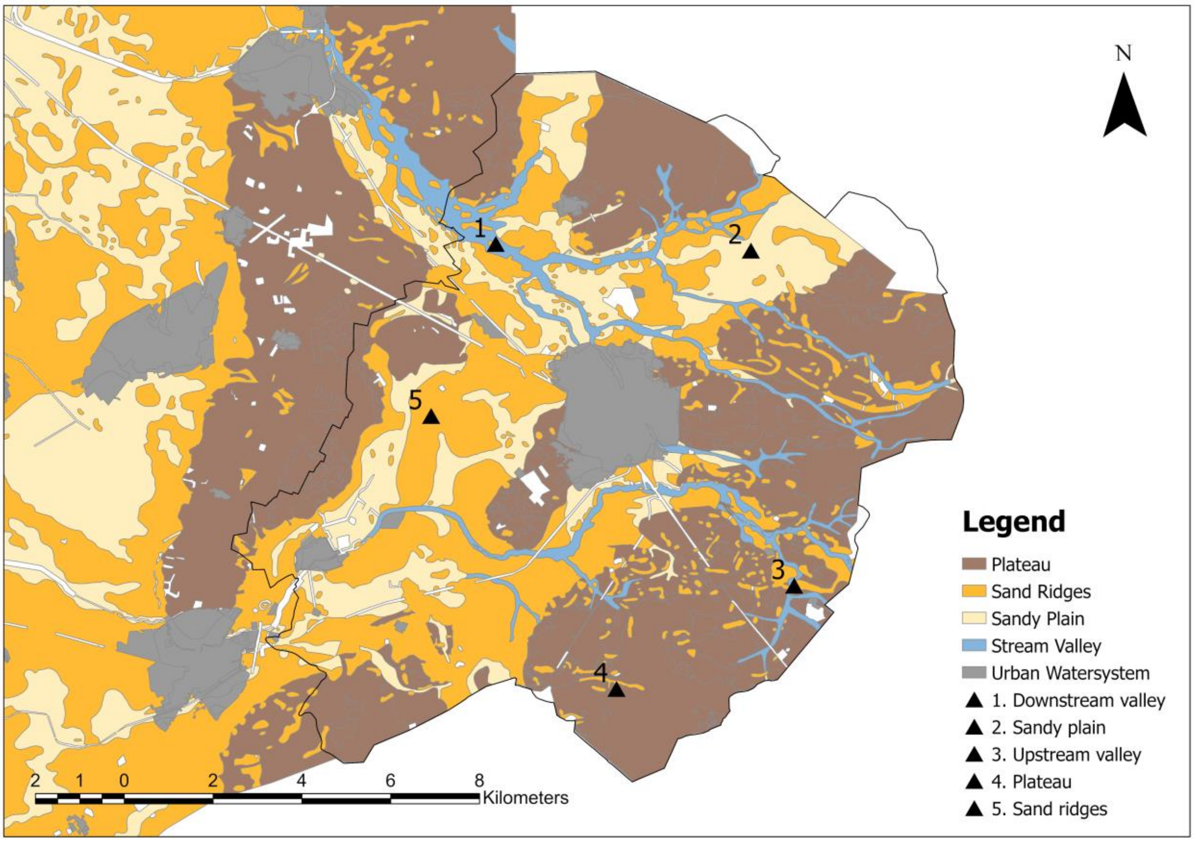


*Figure 4-12 Sample points Winterswijk*

### 4.3.3 Distribution

The distribution of the effect of the reprofiling steps over time was visualized by means of boxplots. The boxplots give an indication on the effect of each reprofiling step in comparison to other reprofiling steps. The outliers of the boxplots gave an indication on whether the reprofiling steps provide sustainable groundwater level increase. Lastly, the process of each reprofiling step gave information on which reprofiling steps attributes the most effect.

### 4.3.4 Comparison

The groundwater characteristics of reprofiling primary or secondary watercourses are compared to reprofiling both watercourses in order to define the effectiveness of each watercourse. This is simply done with the following formula:

$$\frac{X_i}{Y_i} * 100\%$$

X: the groundwater characteristics of reprofiling the primary or secondary watercourses. Y: the groundwater characteristics of reprofiling both watercourses. i: the reprofiling steps of 25%, 50%, 75% and 100%.

All in all, the spatial and time series analysis together with the analysis of the distribution and the comparison are used to answer the first and second sub-question.

### 4.3.5 Agriculture and nature

In order to answer sub-question three, a differentiation has been made between agricultural lands and nature areas, as can be seen in Figure 4-13. Both areas are defined based the land use maps LGN2021[6] of The Netherlands. Appendix A shows which land use types are divided under agricultural areas and which under nature areas. In order to define the effect of reprofiling primary and/or secondary watercourses on the groundwater levels in each area, the increase in mean groundwater levels is compared. The increase in mean groundwater levels for the agricultural and nature area is calculated and compared to indicate which watercourse contributes most to the groundwater increase in these areas. Additionally, a comparison can be made which area experiences the most effect from the reprofiling measures and which area benefits most from combined reprofiling of the primary and secondary watercourses.

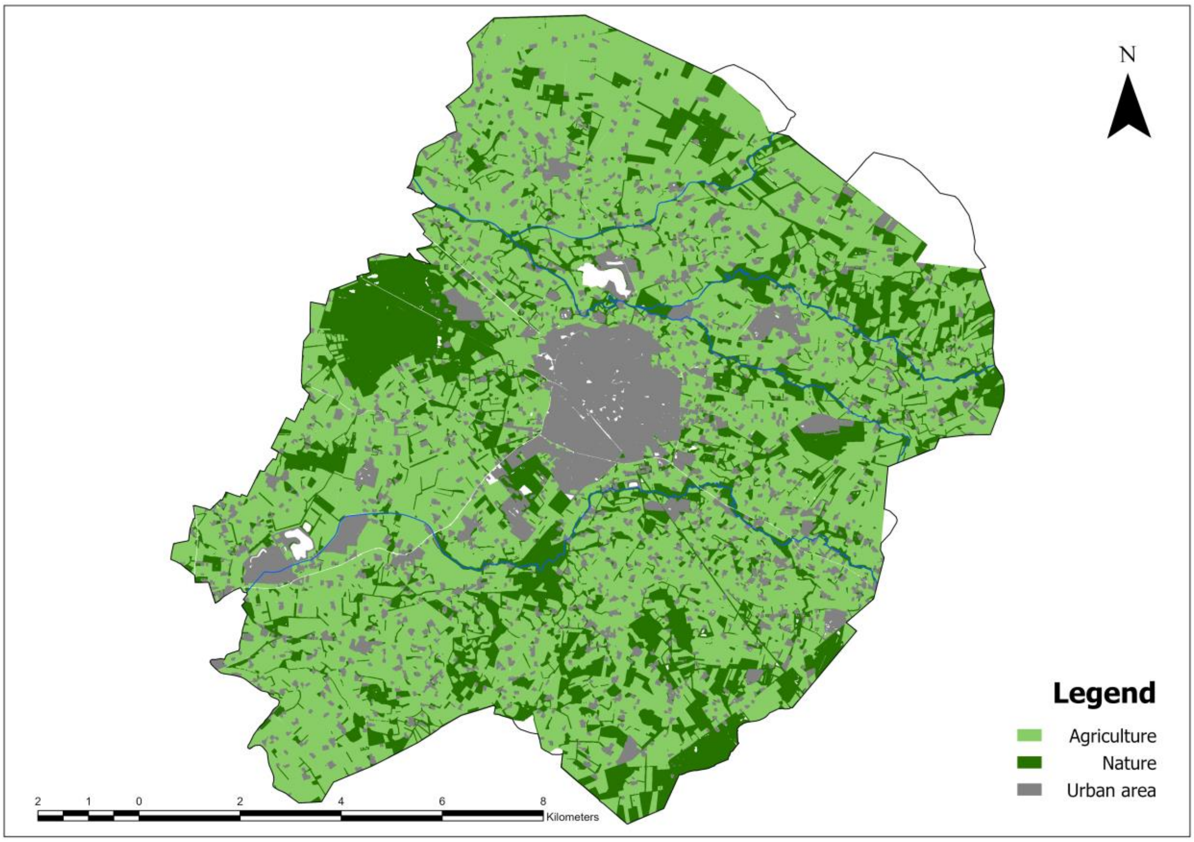


*Figure 4-13 Visualization of the agricultural lands and the nature areas*

Additionally, the contribution of reprofiling the primary or secondary watercourses will be compared to reprofiling both watercourses with equation 4, but only for the agricultural land or the nature area. Lastly, the effect of the primary and secondary watercourses will be compared based on the presence of both watercourses in the area.

[6] Landelijk Grondgebruiksbestand Nederland 2021 (LGN). English: National landuse map of The Netherlands 2021. Website: https://lgn.nl/bestanden

# 5. RESULTS

This chapter elaborates the results of this research. The effect of reprofiling primary and/or secondary watercourses are evaluated based on the spatial distribution, time series analysis, groundwater storage and distribution of the reprofiling steps. A comparison is made between reprofiling primary or secondary watercourses and reprofiling both watercourses simultaneously. Lastly, the effect on nature and agricultural areas is analysed.

## 5.1 MODELLING PRIMARY OR SECONDARY WATERCOURSES

### 5.1.1 Spatial distribution GXG

The effect of reprofiling primary or secondary watercourses in the area of Winterswijk is shown in Figure 5-1. This figure shows the effect of reprofiling the watercourses with 75% on the GLG, GG, and the GVG with regards to the reference scenario over the modelling period of 2012-2020. The spatial effect of each reprofiling step on the GXG can be found in Appendix B.

The effect of reprofiling both types of watercourses is elaborated below, starting with the primary watercourses. The primary watercourses are a dominant part of the water system and attribute largely to the volume of water drainage in the area. Therefore, reprofiling primary watercourses has a significant impact on drainage and subsequently, on groundwater levels. The effect of reprofiling primary watercourses is most visible near the stream valleys and the city centre, followed by the sand ridges and sandy plain, and shown least effective near the plateau. Especially, the larger primary watercourses show the most significant effect, such as along the Boven Slinge and the Groenlose Slinge. This could be due to the larger primary watercourses being characterised by wide and deep riverbeds and thereby generate bigger impact on the groundwater levels than smaller primary watercourses.

The groundwater characteristics increase in effect from GLG to GG and GVG. While the effect on the GVG is larger, the area of effect is more concentrated and locally than the effect on the GG. This could be due to the GVG representing a more extreme average, the spring groundwater levels, while the GG shows an average over the whole year.

The secondary watercourses are smaller in scale, however they are more spread over the area than primary watercourses. Especially agricultural areas often encompass a lot of secondary watercourses to drain the area for proper crop growth. Similar to the primary watercourses a schematization of the GG, GLG and GVG is shown in Figure 5-1. As can be seen the effect of reprofiling secondary watercourses is much smaller and present in other areas than reprofiling primary watercourses. The measure is seen to be most effective in the plateau area, in which there are many secondary watercourses. Also, the primary watercourses showed a larger effect but lower dispersion for the GVG in comparison to the GLG, while the secondary watercourses show both a larger effect and larger dispersion of the effects for the GVG in comparison to the GLG. This could be due to the smaller scale of the secondary watercourses which fill up quicker during a significant rainfall event in spring and therefore affect a larger area.

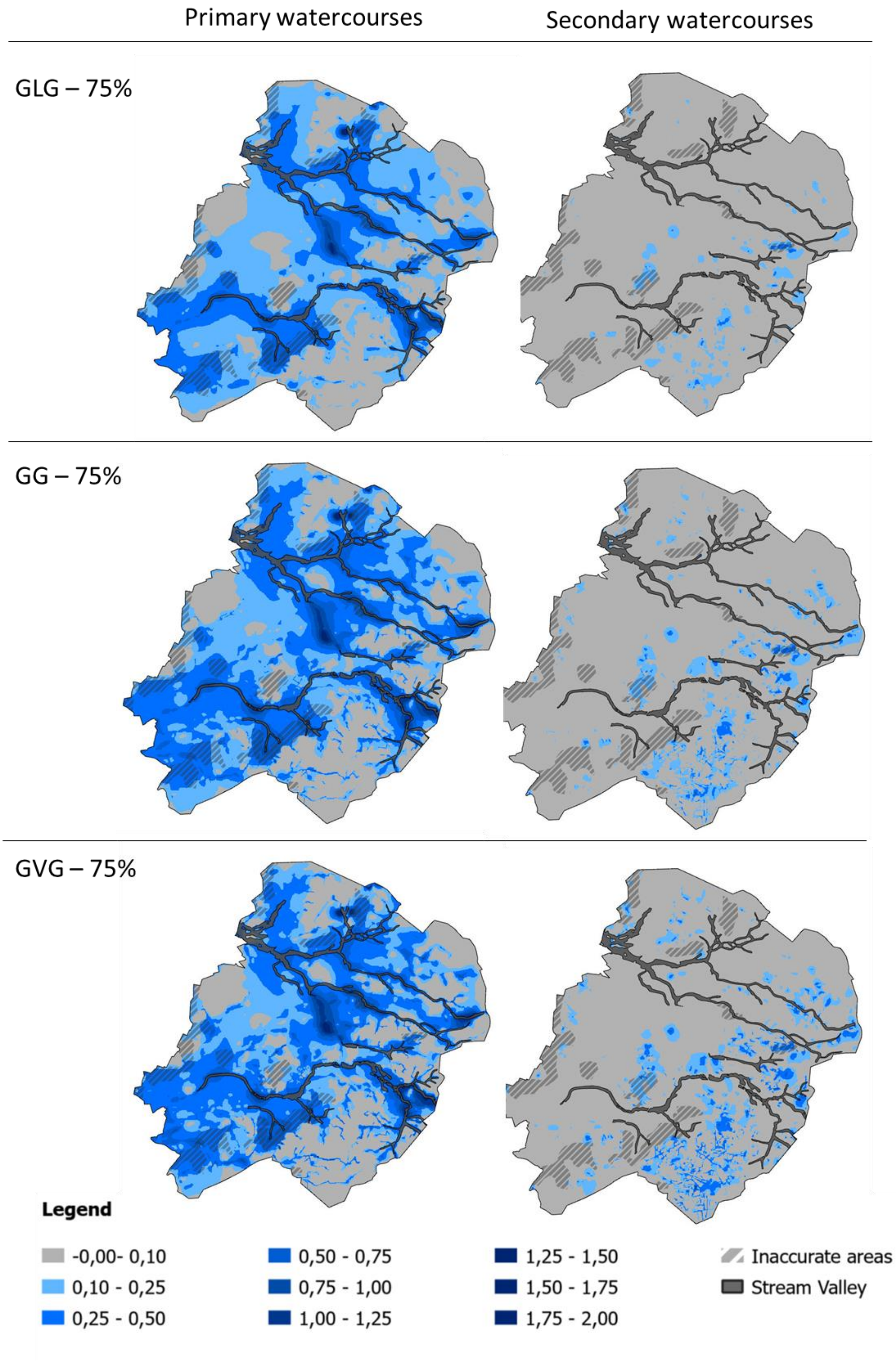


*Figure 5-1 The effect of reprofiling primary and secondary watercourses with 75% on the groundwater characteristics GLG, GG and GVG with regards to the reference level [m]. The stream valleys originate from the water systems map by H+N+S.*

The mean values of the GLG, GG and GVG per reprofiling step for the whole area of Winterswijk are shown below in Table 5-1. As can be seen for the primary watercourses the effect is largest on the GVG except for the first reprofiling step. For the secondary watercourses the effect is largest on the GVG for all steps. Additionally, Table 5-1 amplifies the large difference in effect between the two types of watercourses as reprofiling primary watercourses shows much larger increases than the secondary watercourses.

*Table 5-1 The GLG, GG and GVG over the area of Winterswijk per reprofiling step in mm. PR in bold represents reprofiling primary watercourses and SE not in bold represents the secondary watercourses.*

| | 25% | | 50% | | 75% | | 100% | |
|---|---|---|---|---|---|---|---|---|
| | **PR** | SE | **PR** | SE | **PR** | SE | **PR** | SE |
| GLG | **109** | 16 | **179** | 24 | **220** | 27 | **239** | 30 |
| GG | **126** | 23 | **213** | 35 | **265** | 41 | **288** | 45 |
| GVG | **124** | 28 | **215** | 45 | **272** | 54 | **297** | 60 |

### 5.1.2 Spatial distribution 3XG

When analysing the effect of reprofiling watercourses on reducing the impact of droughts, it is essential to look at the impact it has on the three LG3 in Figure 5-2. For this analysis one wet year (04-2017/03-2018) and one dry year (04-2018/03-2019) have been chosen to evaluate the effect (KNMI - Jaar 2017, n.d.), (KNMI - Jaar 2018, n.d.). The effect on the LG3 for 2017 is larger in volume and spatial distribution for both watercourses, probably due to the significant surplus of precipitation in comparison to 2018. Nevertheless, the effect of reprofiling primary watercourse on the LG3 of 2018 are not minimal and could contribute to decreasing the negative impacts of droughts. The distribution of the effect of reprofiling primary watercourses largely follows the same pattern, near the stream valleys, as in Figure 5-1.

Reprofiling secondary watercourses shows minimal effects for both 2017 and 2018. Due to the small scale of the secondary watercourses the effect and spatial extent of these measures on the LG3 is minimal. After a period of precipitation surplus the secondary watercourses are capable of increasing the groundwater levels, however the LG3 is often experienced after a longer period of drought. A reasonable explanation would be that the primary watercourses take over the drainage function and therefore diminish the impact of reprofiling the secondary watercourses.

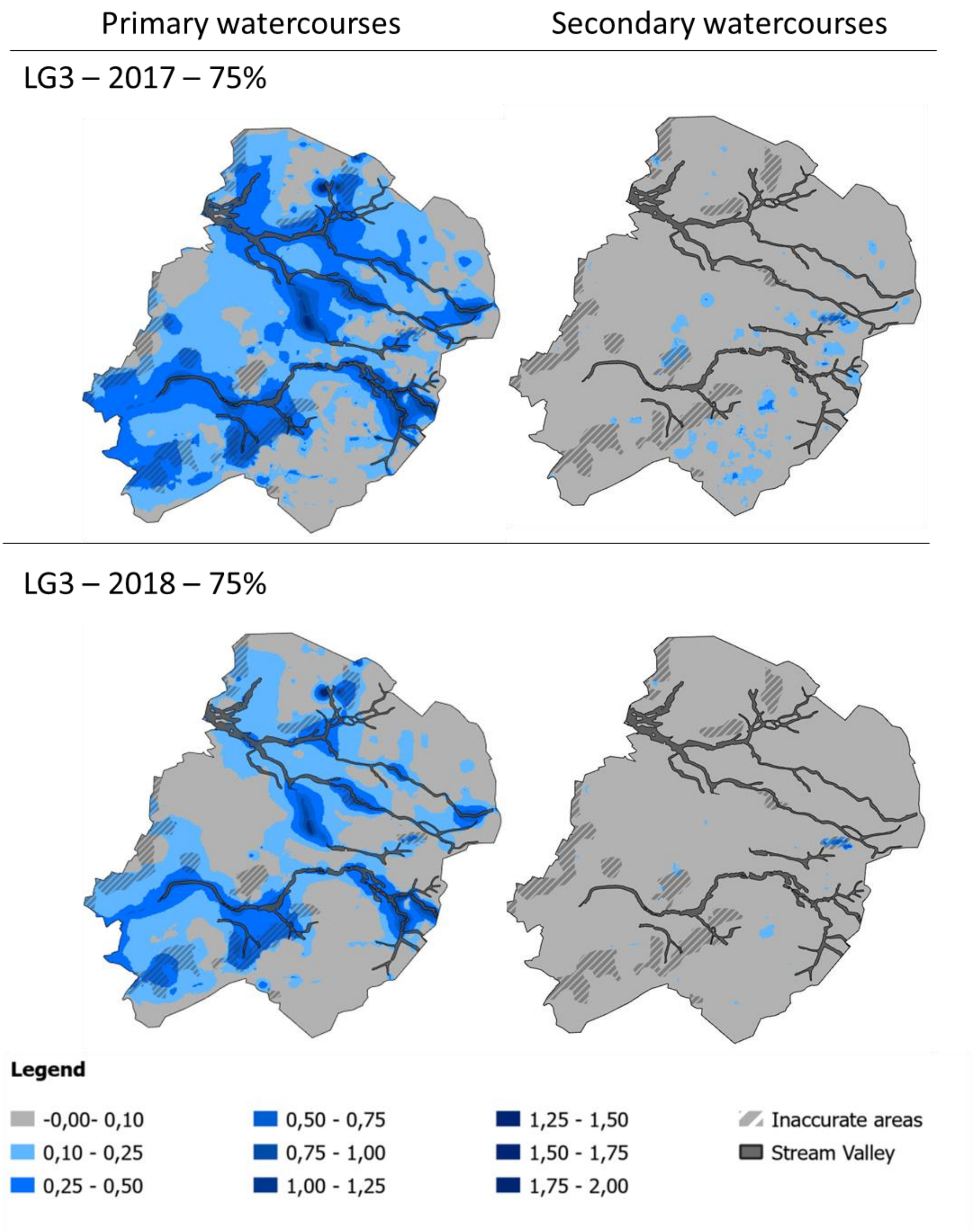


*Figure 5-2 The effect of reprofiling primary and secondary watercourses with 75% on the LG3 in 2017 (upper figures) and 2018 (lower figures)*

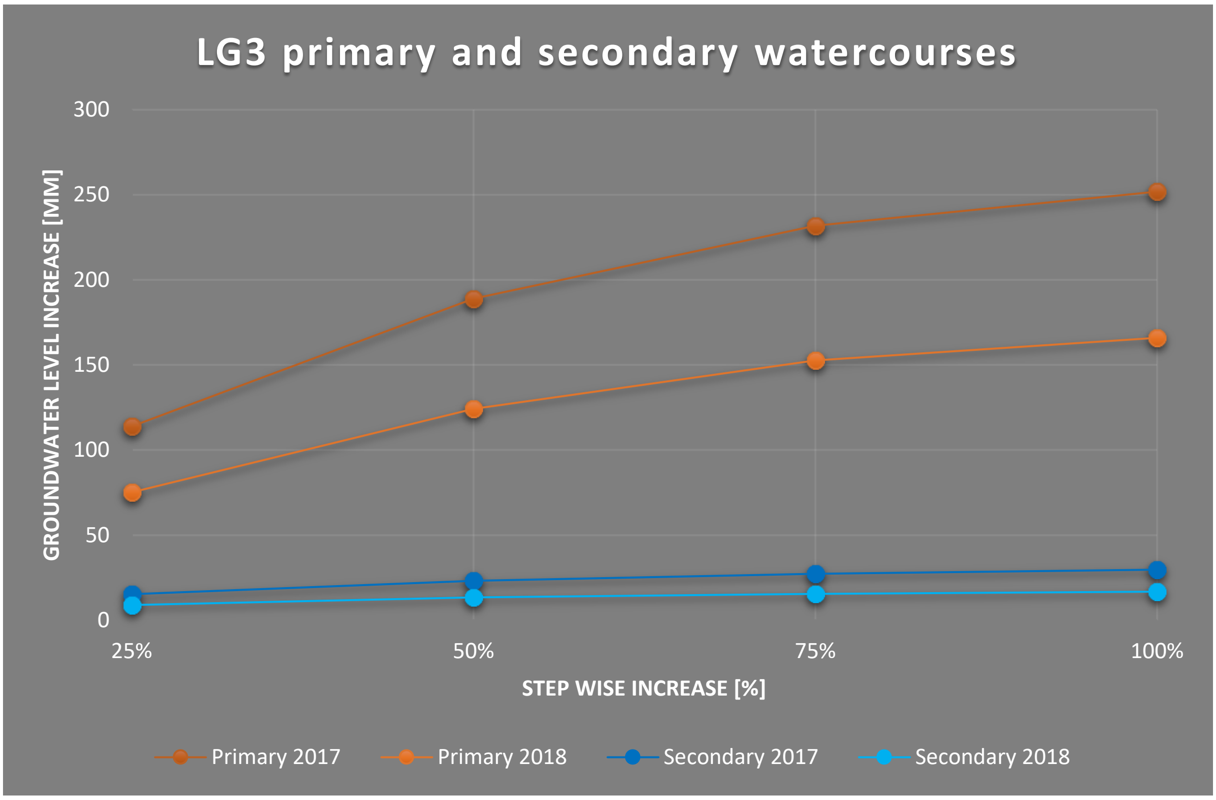


*Figure 5-3 Stepwise increase of the LG3 for reprofiling primary and secondary watercourses in 2017 and 2018*

Figure 5-3 amplifies that the effect of reprofiling primary watercourses on the LG3 is much larger than the effect of reprofiling secondary watercourses. Additionally, there is a stronger increase in the effect of reprofiling primary watercourses per reprofiling step than there is on the secondary watercourses. The difference between each reprofiling step for the secondary watercourses is minimal. The difference between the reprofiling steps of the primary watercourses is more significant and can contribute to mitigating extreme drought conditions.

### 5.1.3 Spatial groundwater storage

The absolute groundwater storage increase of each groundwater characteristic can be calculated, based on the groundwater level increase and the storage coefficient, which leads to the values in Table 5-2. As can be seen, the groundwater storage increases less than the groundwater levels which is most likely because of the heterogeneity of the sandy soil reducing the porosity (Hendriks, 2010). Following the trend of the groundwater levels, the impact is most effective for the GVG and least effective for the LG3 in 2018. The effect of reprofiling the secondary watercourses leads to very little effect on the groundwater storage. The effect is so minimal it might not be taken in to consideration as this can also be due to uncertainties of the model.

*Table 5-2 Mean absolute groundwater storage increase per reprofiling step for each GLG, GG, GVG, LG3 in 2017 and 2018 in mm. PR in bold represents reprofiling primary watercourses and SE not in bold represents the secondary watercourses.*

| | 25% | | 50% | | 75% | | 100% | |
|---|---|---|---|---|---|---|---|---|
| | **PR** | SE | **PR** | SE | **PR** | SE | **PR** | SE |
| GLG | **17** | 3 | **28** | 4 | **34** | 5 | **37** | 5 |
| GG | **19** | 4 | **33** | 5 | **41** | 6 | **45** | 7 |
| GVG | **19** | 4 | **33** | 7 | **42** | 8 | **46** | 9 |
| LG3 - 2017 | **18** | 3 | **29** | 4 | **36** | 4 | **39** | 5 |
| LG3 - 2018 | **12** | 2 | **19** | 2 | **24** | 3 | **26** | 3 |

### 5.1.4 Time series analysis

The spatial distribution of reprofiling primary and secondary watercourses has been made visible. By zooming in on a few sample points, as described in the method, the response of the water system in different areas can be made more clear. The mean groundwater level increase per reprofiling step, per sample point and for reprofiling primary or secondary watercourses is shown in Table 5-3. Interestingly, reprofiling primary watercourses has the least effect on the sample point plateau all other sample points show the least effect from reprofiling the secondary watercourses. Figure 5-5 shows that reprofiling secondary watercourses is more effective for this sample point.

*Table 5-3 Mean groundwater level increase per reprofiling step for each sample point in Winterswijk in mm. PR in bold represents reprofiling primary watercourses and SE not in bold represents the secondary watercourses.*

| | 25% | | 50% | | 75% | | 100% | |
|---|---|---|---|---|---|---|---|---|
| | **PR** | SE | **PR** | SE | **PR** | SE | **PR** | SE |
| 1. Downstream valley | **138** | 8 | **240** | 10 | **308** | 10 | **347** | 10 |
| 2. Sandy plain | **116** | 2 | **180** | 3 | **206** | 3 | **214** | 3 |
| 3. Upstream valley | **455** | 3 | **840** | 4 | **1118** | 5 | **1222** | 5 |
| 4. Plateau | **7** | 20 | **12** | 32 | **14** | 40 | **15** | 47 |
| 5. Sand ridges | **106** | 8 | **140** | 11 | **221** | 13 | **240** | 15 |

The hydrological year at the plateau starts with little to no difference with regards to the reference levels for reprofiling both primary and secondary watercourses. Slowly but steady the difference increases up to the start of December of 2018. In December 2018 a large peak appears contributing to increased groundwater levels, most likely to increased precipitation events in December. In this peak the difference between the reprofiling steps seem to also have gotten larger. The first (25%) and second (50%) step have the largest influence while the effect of reprofiling diminishes with the last two steps (75% and 100%). At the end of the hydrological year the groundwater level for both scenarios decreases back to almost zero again. The little impact of reprofiling measures on the start and end of the hydrological year could be due to the shallow water system at the plateau. In April of 2018 there was a precipitation surplus resulting in the shallow water system of the plateau to be completely filled, therefore the reprofiling measures have little effect during these months.

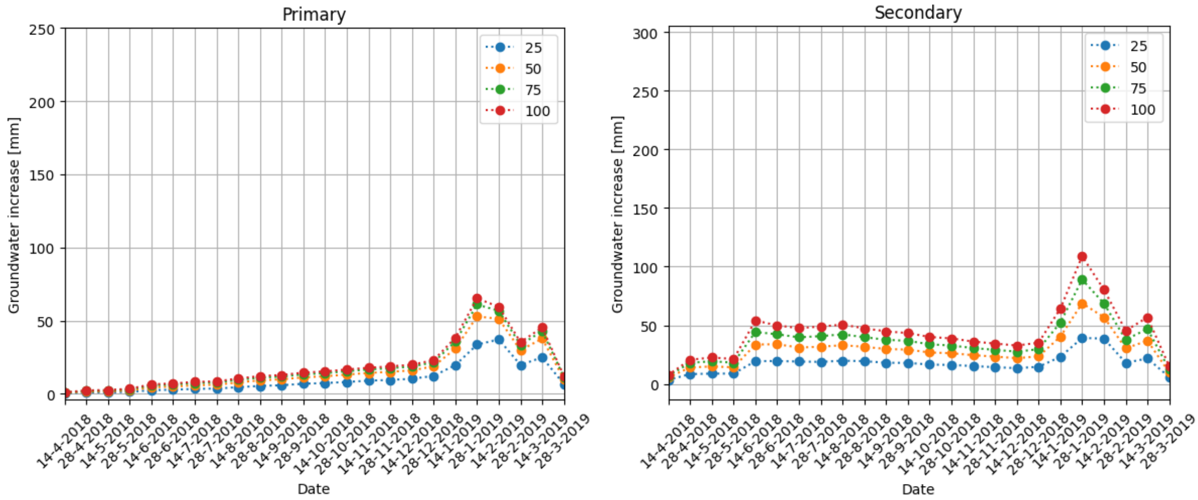


*Figure 5-4 The difference in groundwater level increase with regards to the reference scenario in mm due to reprofiling left) primary watercourses and right) secondary watercourses at the Plateau between 14-04-2018 and 28-03-2019*

When comparing all sample points, the effect of reprofiling secondary watercourses is most beneficial at the sample point Plateau. The effect of increasing water levels starts earlier, in May of 2018, which is beneficial for crop growth since this is often when the precipitation deficit starts to set in. Additionally, the effect of reprofiling secondary watercourses is almost doubled in comparison to the primary watercourses. This phenomenon can be explained by the extensive network of secondary watercourses in this area.

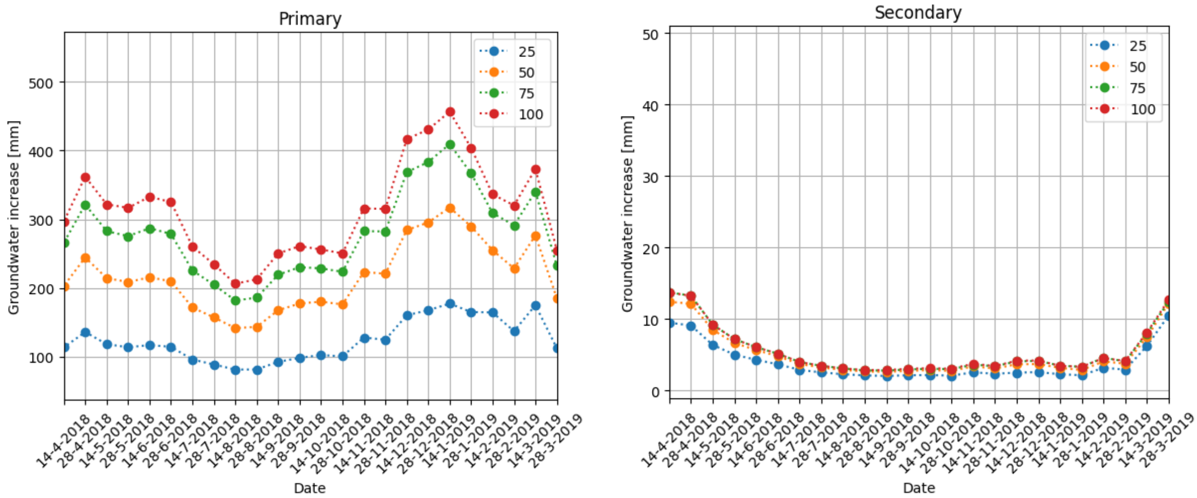


*Figure 5-5 The difference in groundwater level increase with regards to the reference scenario in mm due to reprofiling left) primary watercourses and right) secondary watercourses at the Downstream valley between 14-04-2018 and 28-03-2019*

Each other sample point, besides the plateau, shows a significantly larger effect for reprofiling primary watercourses than for secondary watercourses. An example is the point in the downstream valley, as visualized in Figure 5-7. Important to notice are the different y-axis scales, otherwise the secondary watercourses would not show any fluctuations. Reprofiling the primary watercourses is more effective at this sample point and also shows much more fluctuations throughout the year. Reprofiling the secondary watercourses shows little to no fluctuations, however does have little effect. The fluctuations of the primary watercourses are due to the large scale of this water system and the increased presence of watercourses, therefore responding quickly to changing precipitation events.

### 5.1.5 Distribution of reprofiling steps

The distribution of groundwater level increase of each reprofiling step at each sample point through times is shown in Figure 5-6 for primary watercourses and in Figure 5-7 for secondary watercourses. Firstly, the difference in number of outliers stands out per scenario. Reprofiling secondary watercourses shows significantly more outliers for almost each sample point than reprofiling primary watercourses. This could be due to the small scale of these watercourses, therefore responding more reactive than the primary watercourses. This means that solely increasing secondary watercourses would most likely not result in a sustainable increase of the groundwater levels over time. Reprofiling primary watercourses shows outliers for the sand ridges, sandy plain and the plateau. The sand ridges show a lot of outliers for the primary watercourses because of the large inflow and the deep layer of permeable soil. Significant increase of inflow can therefore cause for more outliers. The sandy plain shows most outliers on the lower end of the sample range for primary watercourses, while the plateau shows most outliers on the upper end of the sample range. This is interesting because both points have similar characteristic with regards how the water system responds. However, the point in the sandy plain is located more closely to the stream valley perhaps resulting in more outliers in the lower end of the samples and the plateau has more elevation perhaps resulting in more outliers in the upper end of the samples. The significant amount of outliers at the plateau for both primary and secondary watercourses could be explained by the fact that it is a shallow system and it therefore responds quickly to input but it also quickly drains. This means that these effects do not result in a sustainable groundwater level increase.

Secondly, the course of the reprofiling steps is clearly made visible in these figures and each sample point shows a version of the pareto principle[7] in which the first steps seem to have the biggest influence and then the effect of the last steps seem to diminish. For the primary watercourses, the steepness of the curve varies from the least steepness for the plateau sample point to the most steepness for the upstream valley. The sand ridges show a bit of a deviation as the largest effect is seen between the reprofiling steps of 50% and 75%. The secondary watercourses show a less clear pareto principle. Most sample points show a rather stagnant and not rising distribution or remain stagnant after the first reprofiling step of 25%. Solely, the sand ridges show a steady increase in the groundwater levels, which could be due to the deep sandy layer being able to uphold a lot of water and not drain as quick.

[7] The pareto principle states the concept that 80% of the effect is often times produced by 20% of the causes (Dunford et al., 2014)

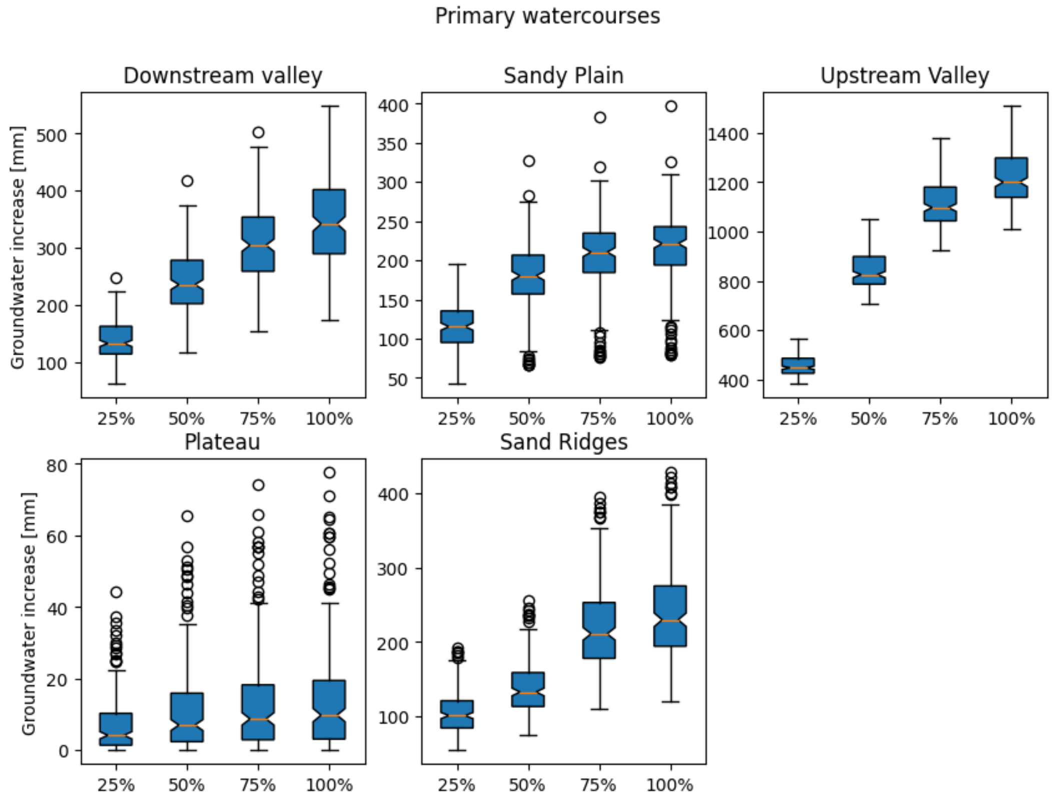


*Figure 5-6 Groundwater level increase distribution of the reprofiling steps for each sample point for reprofiling the primary watercourses*

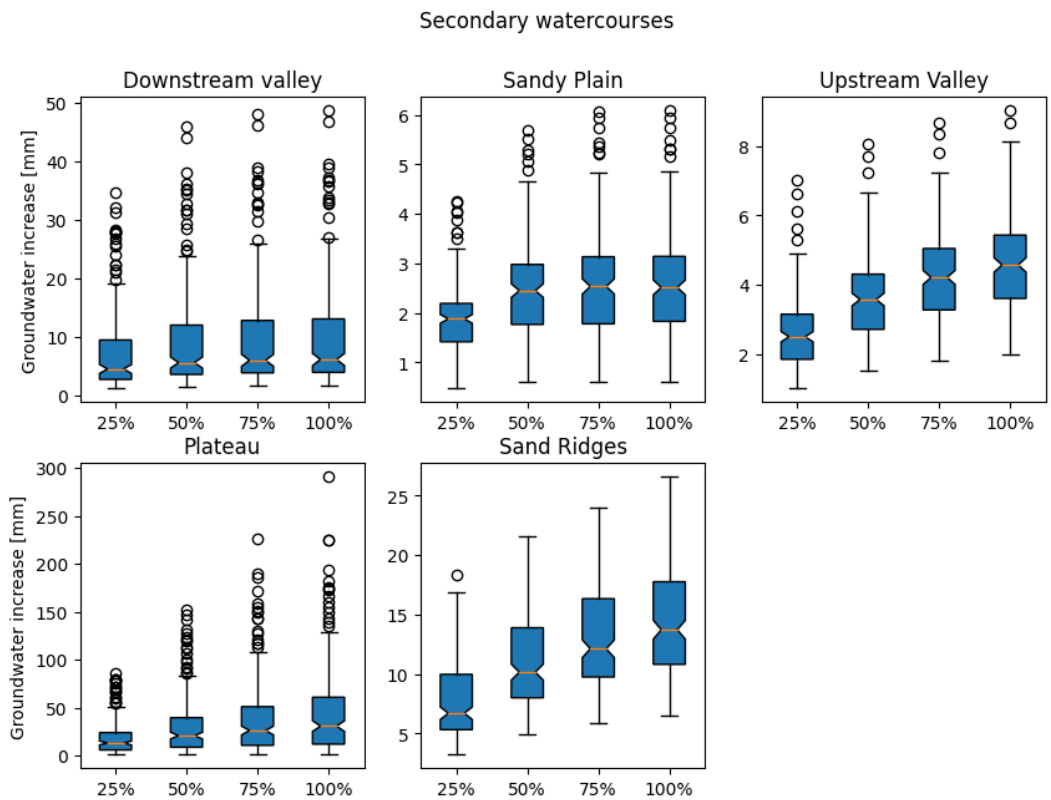


*Figure 5-7 Groundwater level increase distribution of the reprofiling steps for each sample point for reprofiling the secondary watercourses*

## 5.2 MODELLING PRIMARY AND SECONDARY WATERCOURSES

The last scenario consists of modelling the primary and secondary watercourses simultaneously for each reprofiling step. Figure 5-8 shows the distribution of the effect on the GG for the reprofiling step of 100%. Interestingly, the effect of modelling both scenarios together results in a larger effect than solely adding both scenarios. Reprofiling both watercourses simultaneously increases the effect on the groundwater levels.

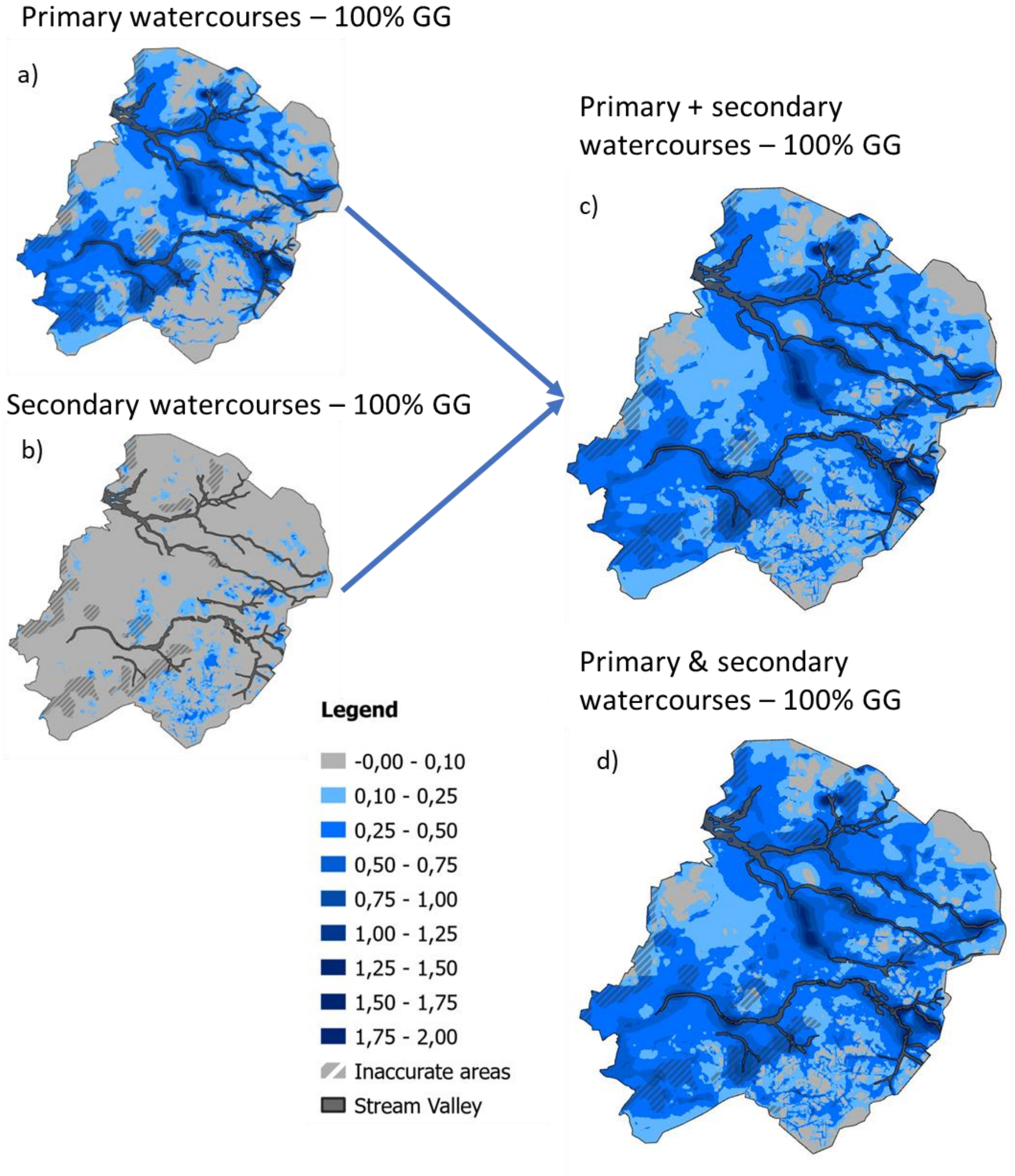


*Figure 5-8 Spatial distribution of a) reprofiling primary watercourses, b) reprofiling secondary watercourses, c) adding the effect of reprofiling primary and secondary watercourses, and d) reprofiling primary and secondary watercourses simultaneously on the GG with regards to the reference scenario.*

The difference between adding the effect of reprofiling primary and secondary watercourses and modelling the effect of reprofiling both primary and secondary watercourses is seen in Figure 5-9. This shows that reprofiling both watercourses results in increased groundwater levels with regards to adding the effect of reprofiling primary and secondary watercourses and thus confirms the effect of interaction between the watercourses. The effect of reprofiling both watercourses has approximately an effect of 100 mm groundwater level increase over Winterswijk and a few areas have an effect of between 100 and 1000 mm groundwater level increase as seen in Figure 5-9.

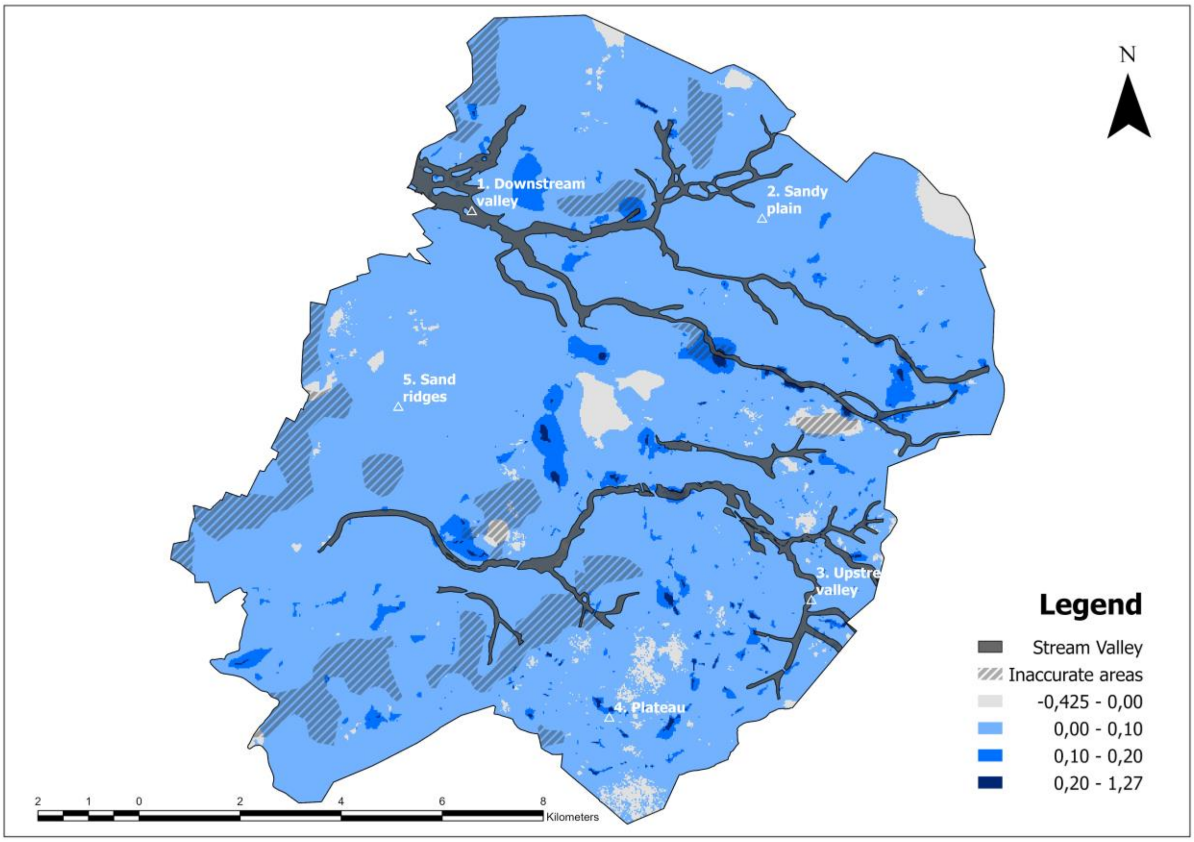


*Figure 5-9 The difference between adding the effect of reprofiling primary and secondary watercourses with 100% and the effect of reprofiling primary and secondary watercourses simultaneously with 100% on the GG.*

The difference between adding the mean groundwater level and storage of reprofiling primary and secondary watercourses versus the groundwater level and storage when modelled simultaneously is shown in Figure 5-10. This figure clearly shows that adding the effect of reprofiling primary and secondary watercourses has a smaller effect than simultaneously reprofiling both watercourses. The difference is quite small at the 25% reprofiling step, but increases with each reprofiling step. The difference in storage remains, however, small.

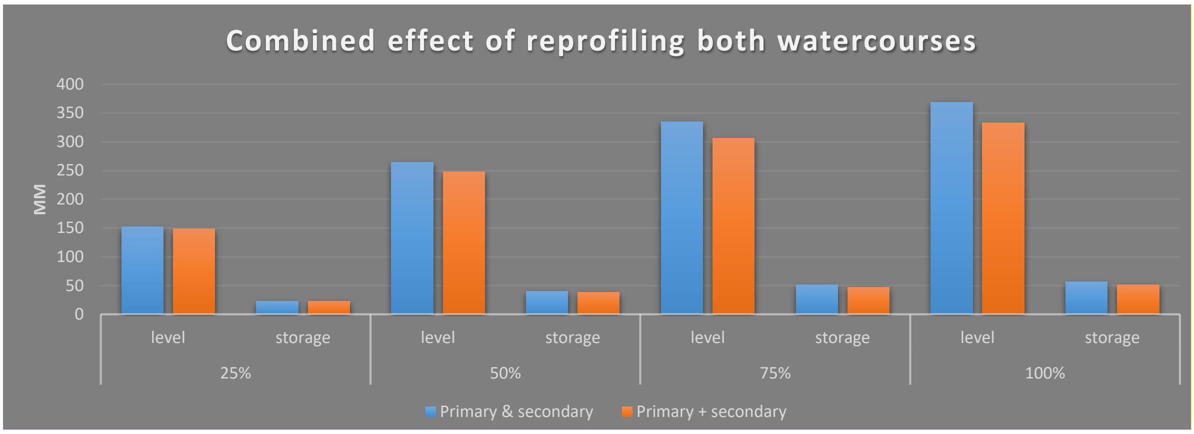


*Figure 5-10 Difference between combined modelling and solely adding the output on average groundwater level and storage over the area of Winterswijk*

Figure 5-11 shows how reprofiling both watercourses simultaneously decreases the amount of outliers in comparison to reprofiling primary or secondary watercourses for the sample point downstream valley and therefore contributes to a more sustainable increase of the groundwater levels.

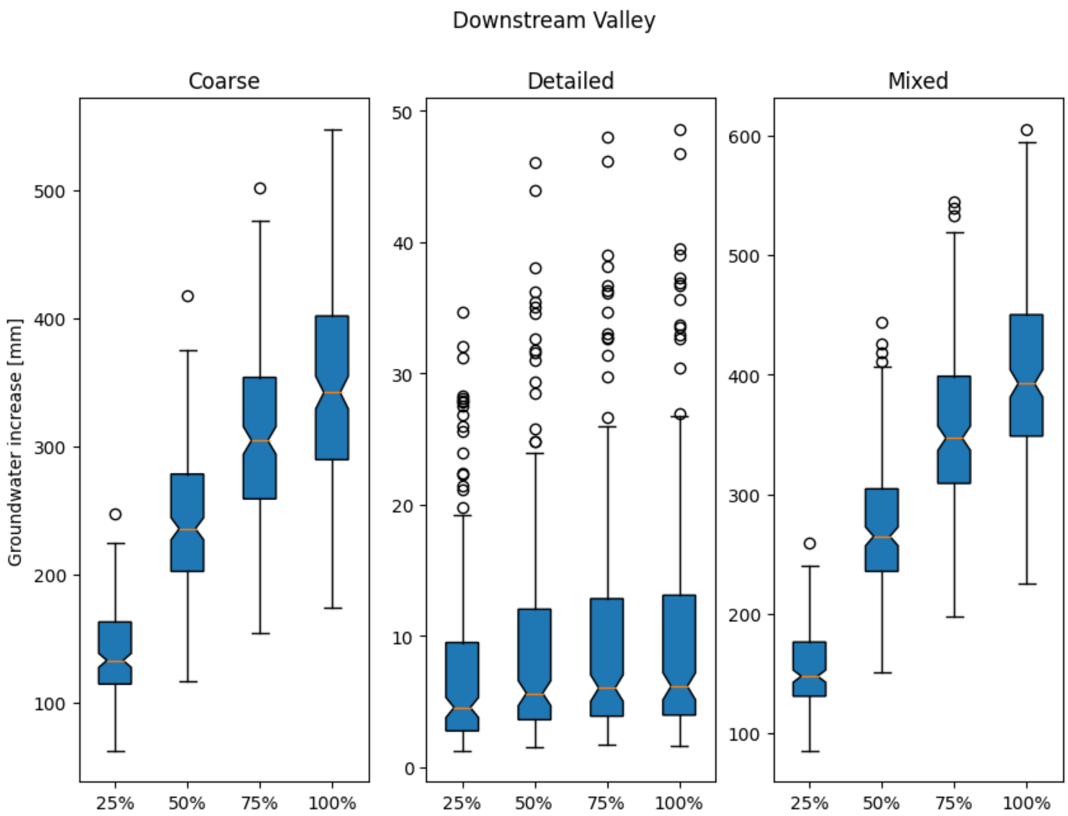


*Figure 5-11 Comparison of the distribution of primary, secondary and primary & secondary watercourses reprofiling effects for the sample point downstream valley*

Lastly, Figure 5-12 shows in what percentage each watercourse contributes to the total effect. Notify that these percentages are based on modelling both scenarios at the same time representing an effect of 100%. Therefore the effect of solely reprofiling primary and secondary watercourses slowly decreases. The figure shows that the ratio between reprofiling primary and secondary water courses is quite similar for the different reprofiling steps. The primary watercourses contribute most to the effect of increasing groundwater levels in comparison to the secondary watercourses.

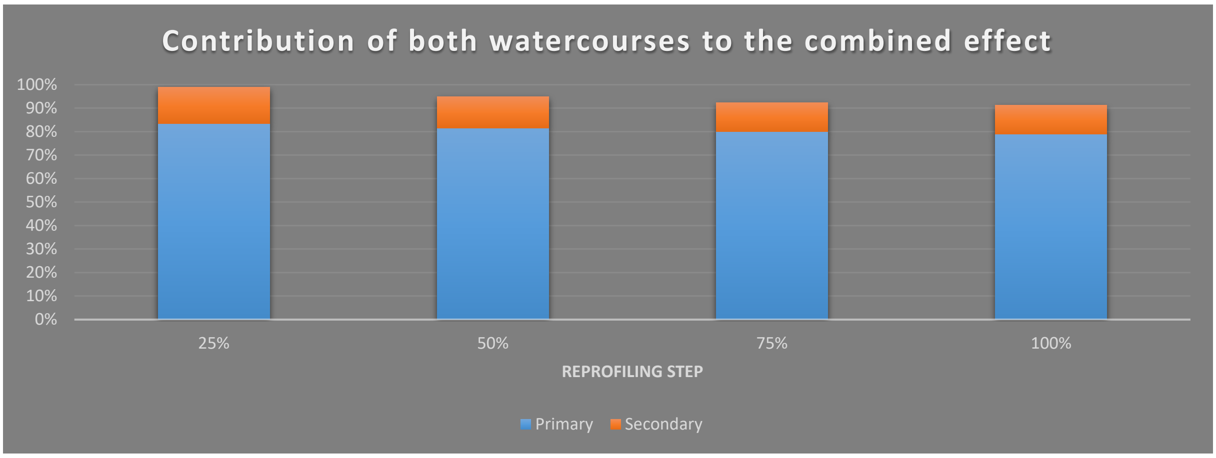


*Figure 5-12 Contribution of each watercourse to the total effect on increasing groundwater levels*

## 5.3 AGRICULTURE AND NATURE

The effect of each reprofiling scenario and step for the two land use types, agriculture and nature, is represented in Figure 5-13. Both land use areas benefit most from reprofiling primary watercourses, and the combination of primary and secondary remains to have the largest impact. Interestingly, the effect of reprofiling secondary watercourses is less effective for agricultural lands than it is for nature areas. This could be due to the secondary watercourses in agricultural lands are strongly connected to primary watercourses that take over the drainage function. In contrast, nature areas are not as connected to the primary watercourses which sustains the effect of reprofiling secondary watercourses in this area.

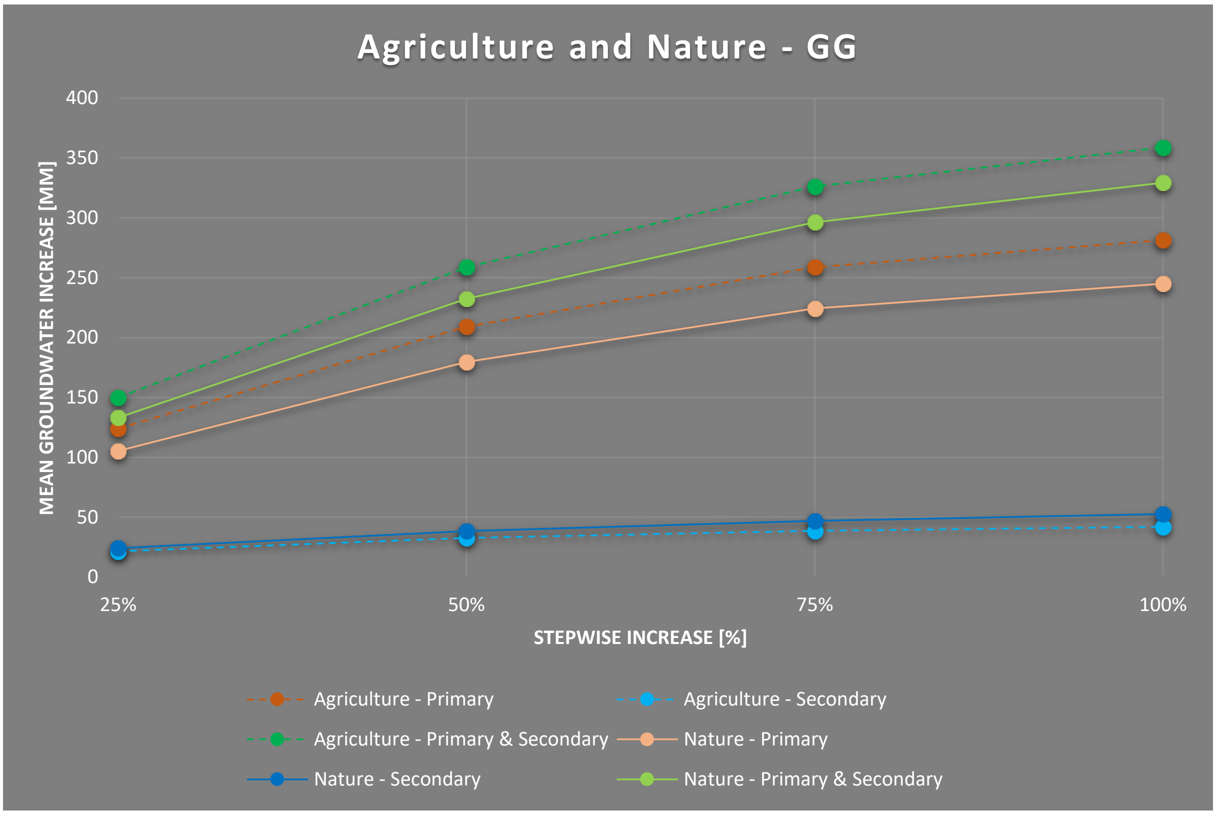


*Figure 5-13 The effect of reprofiling primary, secondary, and primary & secondary watercourses on the agricultural and nature areas.*

Table 5-4 shows the contribution of each watercourse for each land use type. The effect of reprofiling secondary watercourses is more effective for nature areas than it is for agriculture. Furthermore, the continuous decrease is again visible, amplifying the contributed effect of reprofiling both watercourses has on the groundwater levels.

*Table 5-4 Contribution of each watercourse for each land use area*

| | 25 | | 50 | | 75 | | 100 | |
|---|---|---|---|---|---|---|---|---|
| | **Agri** | Nat | **Agri** | Nat | **Agri** | Nat | **Agri** | Nat |
| Primary | **83%** | 79% | **81%** | 77% | **79%** | 76% | **78%** | 74% |
| Secondary | **14%** | 18% | **13%** | 17% | **12%** | 16% | **12%** | 16% |

While the effect of primary watercourses is larger for both areas, primary watercourses are only present in 30% of the total model grid cells representing watercourses in comparison to 70% of the grid cells representing secondary watercourses. This applies to both nature and agricultural lands. Therefore the large contribution of primary watercourses might not be due to their spatial presence but more logically due to their larger width and depth. Additionally, when looking at the total conductance present from both watercourses in the agricultural area, the primary and secondary watercourses represent both 50% of the conductance. In the nature areas 60% of the conductance is due to the primary watercourses, while the secondary watercourses contribute for 40% to the total conductance.

In Figure 5-14 the effect of both measures on both land use types is made visible. While Table 5-4 indicates that the effect of reprofiling secondary watercourses is more effective in nature areas than in agricultural areas, Figure 5-14 shows that the effect of primary watercourses remains significant also for the nature areas. This could be due to the relatively large effect of primary watercourses with regards to secondary watercourses. While primary watercourses provide less effect on nature areas than on agricultural areas, the effect is still significantly larger than the effect of secondary watercourses.

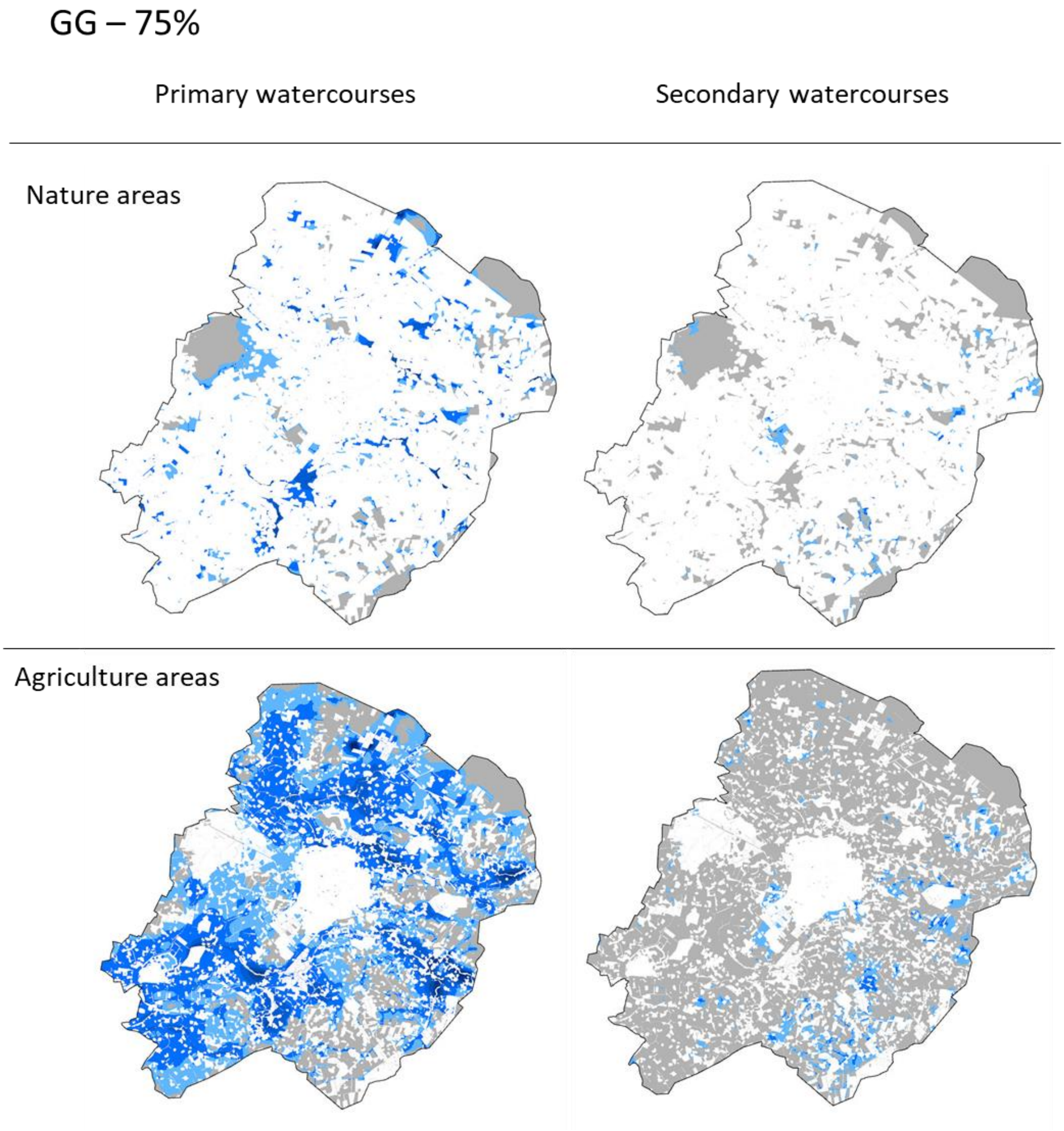


*Figure 5-14 The effect of reprofiling primary or secondary watercourses with 75% on the GG in nature and agricultural areas. The upper two figures represent the nature areas and everything else is made white. The lower two figures represents the agricultural areas and everything else is made white. A part of the research area in Germany is kept visible in both figures.*

# 6. DISCUSSION

This chapter discusses the results and relates them the existing body of literature, while also discussing the unintended effects of reprofiling watercourses. The limitations, assumptions and uncertainties are put in perspective of the results and lastly recommendation for further research are made.

## 6.1 DISCUSSION OF THE RESULTS

The severity of drought issues increases, affecting the livelihoods of millions of people and causing significantly economic damage (Spinoni et al., 2013; Dai, 2010). The Achterhoek in The Netherlands is especially troubled by drought events such as experienced in 2018 (Daniels et al., 2013), (Philip et al., 2020). Climate predictions by the KNMI expect such drought events to occur more often in the future (Van den Hurk et al., 2014). Therefore, it is essential to redesign the water system in order to store more water for future drought events. While going back to a state with no drainage, as in history, is not possible, other redesigning measures need to be explored. The results of this study indicates that redesigning, respectively reprofiling, watercourses can increase groundwater levels and storage and therefore reduce the impact of droughts, which is in line with the studies of Van den Eertwegh et al. (2021) and, Querner and Van Lanen (2001).

Reprofiling primary watercourses logically generated the largest increase of groundwater levels in comparison to secondary watercourses which was also stated by Van den Eertwegh et al. (2021). This could be due to larger dimensions of the primary watercourses. Nevertheless, reprofiling secondary watercourses is not without effect and does increase groundwater levels as supported by literature from Querner and Van Lanen (2001). The effect of solely reprofiling secondary watercourses is largely diminished due to the primary watercourses taking over the drainage function as also stated by Van den Eertwegh et al. (2021). The effect of reprofiling primary watercourses is seen most effective near primary watercourses and the effect of reprofiling secondary watercourses is shown most effective near secondary watercourses.

While the effect of reprofiling primary watercourses generates increased groundwater levels throughout the whole hydrological year the effect of reprofiling secondary watercourses is mostly seen after a longer period of precipitation. Van den Eertwegh et al. (2021) showed similar results as the impact of secondary watercourses was seen most effective in March. Nonetheless, this study showed that this depends on the location as the sample point plateau does not show an increase during the normally wet months (December-March) but during the normally dry months (June-December). This could be due to the plateau consisting of a thin permeable layer and the drainage volume of the watercourses being remained. Therefore, during wet months the water is completely drained. While during dry months the groundwater level might have dropped below the bed of the watercourse and reprofiling the watercourses does contribute to increased groundwater levels with regards to the reference scenario. Reprofiling secondary watercourses seems to have little effect on extreme drought situations such as the LG3 of 2018. This is in line with literature of Van den Eertwegh et al. (2021) stating that the effect of secondary watercourses is diminished after a longer period of drought. The LG3 often happens after a long period of drought and the extra storage raising the bed and level of the secondary watercourses would have made, have probably vanished due to the primary watercourses taking over the drainage function.

The effect of reprofiling both watercourses simultaneously created the most effect on groundwater level increase, suggesting that it would be beneficial to reprofile them both as supported by literature such as Van den Eertwegh et al. (2021) and Querner and Van Lanen (2001). However, this study showed that the combined effect depends on whether the area also represents both watercourses.

The results of the time series analysis of various sample points showed a difference between the fluctuations of the groundwater level increase throughout the year. Some areas showed significant fluctuations in groundwater levels while others responded more slowly. This is also supported by Van den Eertwegh et al. (2021) as was stated that heavily drained areas, such as Plateau, respond quickly, while little drained areas, such as sand ridges, responds less reactive. The difference between the effect of reprofiling measures on the nature and agricultural areas were interesting as the expectation was that the agricultural areas would benefit more from reprofiling secondary watercourses as these areas are dominated by secondary watercourses. However, probably the impact of such large watercourses are more dominant than the presents of a lot of smaller watercourses. Lastly, while the groundwater levels increased the absolute groundwater storage remains little, which might be due the mainly sandy soil (Cultuurtechnische Vereniging, 1987). Lastly, the distribution of the effect over each reprofiling step was in line with the expectation of the pareto principle (Dunford et al., 2014). Most effect was seen for the first reprofiling steps, while the effect diminished for the last reprofiling steps. This could be applicable to other reprofiling measures of watercourses which would in then indicate that not always the most extreme reprofiling step is necessary to provide significant effect.

### 6.1.1 Unintended effects

The focus of this study was researching the effect of reprofiling watercourses on mitigating the negative impacts of droughts. Therefore the results were focused on the mean lowest, spring and average groundwater levels. However these reprofiling measures also impact the highest groundwater levels in the area which can result in nuisance. The negative values in Figure 6-1 shows the areas where the GHG increases above surface level due to reprofiling both watercourses with 100% and thus causes nuisance. The largest effect is seen near the Korenburgerveen, which is a wet nature area and therefore probably not experienced as negative. The plateau area, which is mainly agricultural lands, experiences quite some nuisance, which could hinder farmers. Looking at the effect of reprofiling both watercourses with 100% on the GG there are less groundwater levels above surface level experienced, meaning in average situations little nuisance would occur. Additionally, groundwater levels that do not succeed surface level can still cause hinder for example in the urban area. The guideline for the urban area states that the groundwater levels can't exceed 70 cm below surface level (SBR publication 99, 'Bouwrijp maken van terreinen' cited from (Grontmij & KPMG, 2001)). As seen in Figure 6-1 the urban area does experience GG and GHG values higher than 70 cm below surface level.

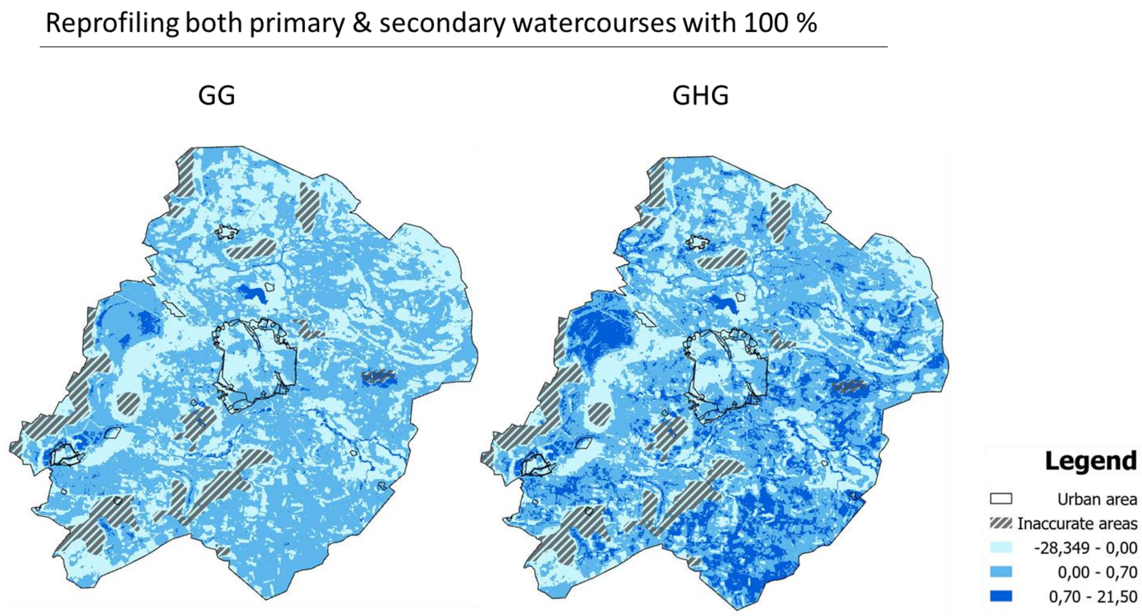


*Figure 6-1 The effect of reprofiling both the primary and secondary watercourses with 100% on the GG and GHG with regards to surface level [m]*

## 6.2 Research implications

The results show that these reprofiling measures contribute to increased groundwater levels sufficiently to fulfil the aim of 10-50 groundwater level increase and thus contribute to the so called ‘sponge’ effect in this area as emphasized by the governmental letter of Harbers (2022).

However as mentioned, the aim of multiple parties in the east of The Netherlands is to increase groundwater storage with 100 mm, based on two reasons. Firstly, the difference in groundwater storage between the GHG of 1950 and now is approximately 100 mm according to LHM calculations by (*Bijlage D Feitenbeeld Watersystemen Achterhoek*, 2021). Secondly, the future KNMI climate scenarios of 2050 predict an average and extreme precipitation deficit of respectively 185 mm and 290 mm (Van den Hurk et al., 2014). According to (*Bijlage D Feitenbeeld Watersystemen Achterhoek*, 2021) Winterswijk has enough storage to manage a precipitation deficit of 140 mm, which is why another extra 100 mm storage would suffice to compensate for the predicted average and partly the extreme precipitation deficit.

The results show that reprofiling both watercourses with 100% resulted in approximately 56 mm absolute groundwater storage increase and therefore does not meet the aim of 100 mm. Further research is required to identify what other (reprofiling) measures are needed to achieve this aim. Other reprofiling measures could consist of raising the river bed with steps of magnitude until surface level is reached, ultimately filling up the watercourse. This would result in decreasing the drainage volume and therefore more extremely effect the GHG or widening the watercourse and therefore take up more space. Further research could also investigate whether 100 mm extra groundwater storage is achievable for the whole area of Winterswijk. The results of the increased groundwater storage can be compared to the precipitation shortage. Figure 6-2 shows, among others, the precipitation shortage of 20-06-2023. The current precipitation shortage is 155 mm and reprofiling both watercourses with 100% would reduce the impact on with approximately 56 mm. The precipitation shortage would have been reduced with approximately 33% which is significant as an addition to the current groundwater storage. Nevertheless, this is a only one day and does not represent the whole year.

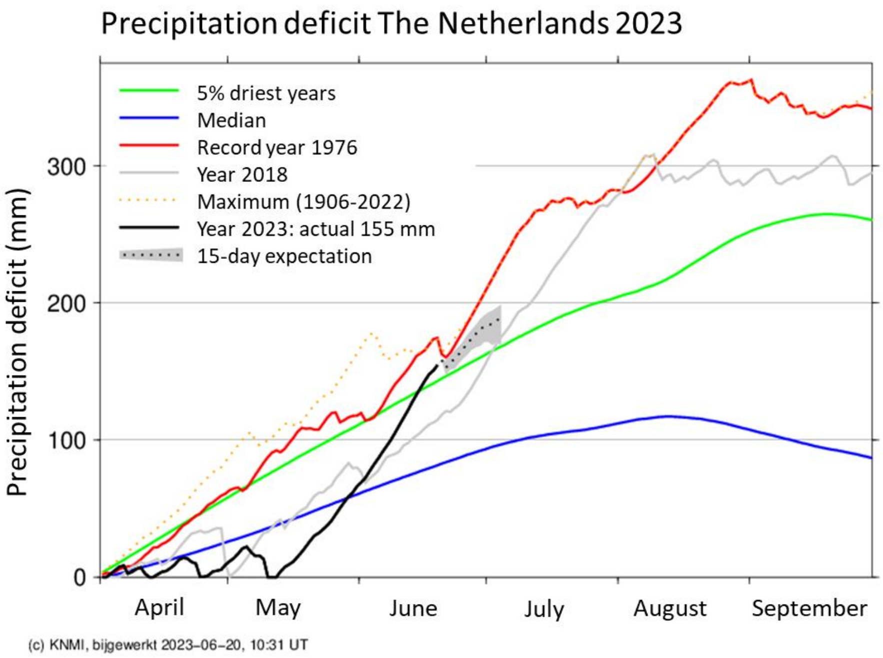


*Figure 6-2 Precipitation shortage in The Netherlands for 20-06-2023, adjusted from (KNMI - Neerslagtekort / Droogte, n.d.)*

The growing season starts around the same time as the hydrological year, in April and is defined as the period between bud burst and leaf fall (Van den Eertwegh et al., 2021), (Linderholm, 2006). Often problems of drought with regards to crops don't start simultaneously with the start of the growing season but later on when precipitation reduces and temperatures rise. Therefore, in order for the agricultural lands to benefit from increased groundwater levels, the effect of reprofiling should persist longer than the first two months of the growing season. The time series analysis of the sample points show that for almost each point the groundwater levels remain increased with regards to the reference level. Thereby contributing to mitigation of drought in agricultural lands. However, the results of the GHG in 6.1.1. showed possible nuisance, which could lead to crop damage due to overwatering.

## 6.3 Limitations, assumptions, and uncertainties

### 6.3.1 Model limitations

All groundwater models are a simplification of reality and the complete elaboration of limitations and assumptions made in Amigo can be found in the rapport of De Weme et al. (2019). The first limitation of this model originates from the inaccurate areas, as mentioned in the method, produce too low groundwater levels. These areas were made visible in the spatial distribution, however were not excluded from calculating the mean spatial groundwater characteristics. The inaccurate areas take up approximately 9% of the total area of Winterswijk. Additionally, inaccuracy has been found for runoff in the urban area. Due to inaccurate interaction between the two model codes, MODFLOW and MetaSWAP, and a ponding depth of 999 in MetaSWAP of the urban area in Amigo, the water column in this area infinitely increased until a certain threshold was reached and the overland flow package of MODFLOW took over (Arens, 2023). This resulted in inaccurate peaks in groundwater levels for the urban area. While this study not specifically focussed on the urban area, the groundwater output from the urban area were not excluded from calculating the mean groundwater characteristics. However, excluding both inaccuracies would underestimate the effect of reprofiling watercourses on the groundwater level and storage.

The storage coefficient used in this research originates from a project of Witteveen+Bos. The storage coefficient has been calculated based on average values between half of March and half of April over the model period 2012-2019. However, the storage coefficient is, among other things, dependent on the groundwater level with regards to the surface level (Cultuurtechnische Vereniging, 1987), (Hendriks, 2010). In this study reprofiling measures have been modelled to increase groundwater levels, which is why the storage coefficient might be less accurate for these new situations. However, while the storage coefficient might not be completely accurate it does give a good approximation of the impact reprofiling watercourses has on groundwater storage.

### 6.3.2 Scenario assumptions

In Amigo the watercourses are represented by the following parameters: height of the riverbed, river conductance, water level in the river, and the infiltration factor. The conductance is dependent on the wetted perimeter of the watercourse, the length of the watercourse in the model cell and the river bed resistance. For the reprofiling scenarios the assumption has been made that the watercourses are rectangle shaped. Therefore, raising the river bed and water level in the watercourses does not alter the wetted perimeter and conductance. This reduced the uncertainties of recalculating the conductance values. However, the ISG data of Amigo model showed that each river segment has its own unique trapezium watercourse shape. Raising the river bed and water level in Amigo resulted in a watercourse as visualized in Figure 6-3 b). This indicates that the watercourse narrows during the reprofiling steps. However, practically watercourses are heightened in as Figure 6-3 c). This modelling choice therefore probably results in more effect on the groundwater levels than Figure 6-3 c) would generate.

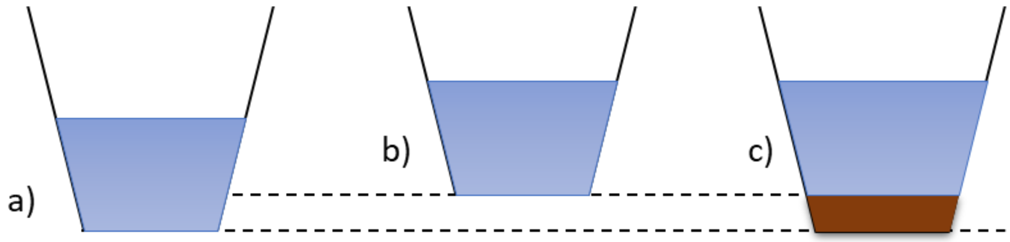


*Figure 6-3 Visualization of a watercourse in Amigo, a) current watercourse, b) heightened watercourses in Amigo, c) heightened watercourse in practice*

## 6.4 Recommendations and further research

The study has analysed the effect of reprofiling watercourses on groundwater levels to mitigate drought. However, further research is required to gain a more comprehensive view of which measures are most effective for different type of areas. In this study an initial analysis has been done on the impact of reprofiling watercourses on the agricultural and nature areas. However, clear consequences for these areas require further research. More detail on the impact of these areas can be researched based on the tools “Waterwijzer Landbouw” and “Waterwijzer Natuur”. Especially for agricultural areas it is important to find a balance between mitigating drought and reducing nuisance.

Additionally, further research could include more sample points for each water system in Winterswijk. For this study one sample point has been chosen to represent the different water systems in Winterswijk and to visualize how different spatial points can respond differently. However, since the sample points have shown such a large variation in response to either reprofiling primary or secondary watercourses it would be interesting to further this research. In order to correctly represent a water system a larger sample size should be taken to analyse the response to reprofiling measures. Additional research on the response of different water systems to reprofiling measures could provide valuable information for future water management.

Another deviation of this research could be to focus on reprofiling the watercourses in a different manner. For example, it might be interesting to study the effect of raising the riverbed without raising the water level in the watercourse. Another option would be to study the effect of meandering the watercourses to prevent extensive drainage. Or researching the effect of different shapes of the watercourse, such as an accolade profile has been found to be very useful in decreasing drainage while preventing nuisance (Van den Eertwegh et al., 2021). The measures researched in this study are realistically, however the measures as mentioned above are more extreme, could also lead to interesting insights to reduce drainage. Further research could also be focused on other type of measures to mitigate drought such as altering drainage in urban areas, increasing water storage in sand ridges or decreasing groundwater irrigation. Lastly, the aim of increasing groundwater storage with 100 mm might not be as feasible for every area and therefore further research in changing land use accordingly to the existing drought or nuisance situation might be more efficient.

# 7. CONCLUSION

This research aimed to provide insights on the effect of reprofiling watercourses on groundwater levels and storage. The central question for this research were as follows:

*How does reprofiling watercourses influence groundwater levels and mitigate drought impacts in nature and agricultural areas?*

Based on groundwater modelling in Amigo it can be concluded that reprofiling, by raising the bed and water level, of watercourses contributes to increased groundwater levels and storage in Winterswijk. As a result of the fine scale groundwater model (25 meter by 25 meter) a detailed comparison was made between the effect of reprofiling primary or secondary watercourses.

Reprofiling primary watercourses has shown to be more effective in increasing groundwater levels and subsequently groundwater storage than reprofiling secondary watercourses. Both nature and agricultural areas experienced a greater impact from reprofiling primary watercourses. All in all, simultaneously reprofiling both watercourses was most effective, as supported by literature. Additionally, the results suggest that the effectiveness of reprofiling different types of watercourses depends on the water system, respectively the soil structure, elevation and main watercourses in that area. While most sample points benefited from reprofiling primary watercourses, one sample point benefited most from reprofiling secondary watercourses. Therefore, water managers would benefit from taking the water system in consideration before deciding on reprofiling measures. Additionally, the effectiveness of reprofiling seemed to diminish during the last reprofiling steps, confirming the pareto principle that most effect is seen with the first reprofiling steps. This could therefore also be expected for other reprofiling measures, and taken in consideration when deciding what magnitude of reprofiling measures needs to be applied. Nevertheless, the sample points did show a variation in the distribution over the reprofiling steps thus again the water system needs to be taken in to consideration when looking at which magnitude of reprofiling needs to be applied.

For this study the choice has been made to reprofile the watercourses while maintaining the same drainage volume. Therefore, these measures are not very extreme. Nevertheless, the measures have shown to be effective in increasing groundwater levels and storage and subsequently mitigating drought. This is promising for the effectiveness of reprofiling watercourses and further research on reprofiling measures. Based on these conclusions, water managers should critically evaluate the water system of an area before choosing reprofiling measures. Lastly, the considerable effect of these relatively less extreme measures indicates that aiming for 100 mm extra groundwater storage might not be as inaccessible. However, further research is needed to study which other reprofiling measures can contribute to this ‘no-regret’ 100 mm extra groundwater storage in order to mitigate drought in the Achterhoek in The Netherlands.

The insights of this research contribute to increase the knowledge on how the water system responds to reprofiling watercourses and subsequently can help mitigate droughts in the long term. This research has contributed to the limited modelling studies with regards to exploring different drought mitigation measures and hopefully stimulated interest in further exploring alternative reprofiling measures. All in all, this research has shown that reprofiling measures can make a significant impact on groundwater levels and thereby prepare for future climate scenarios.

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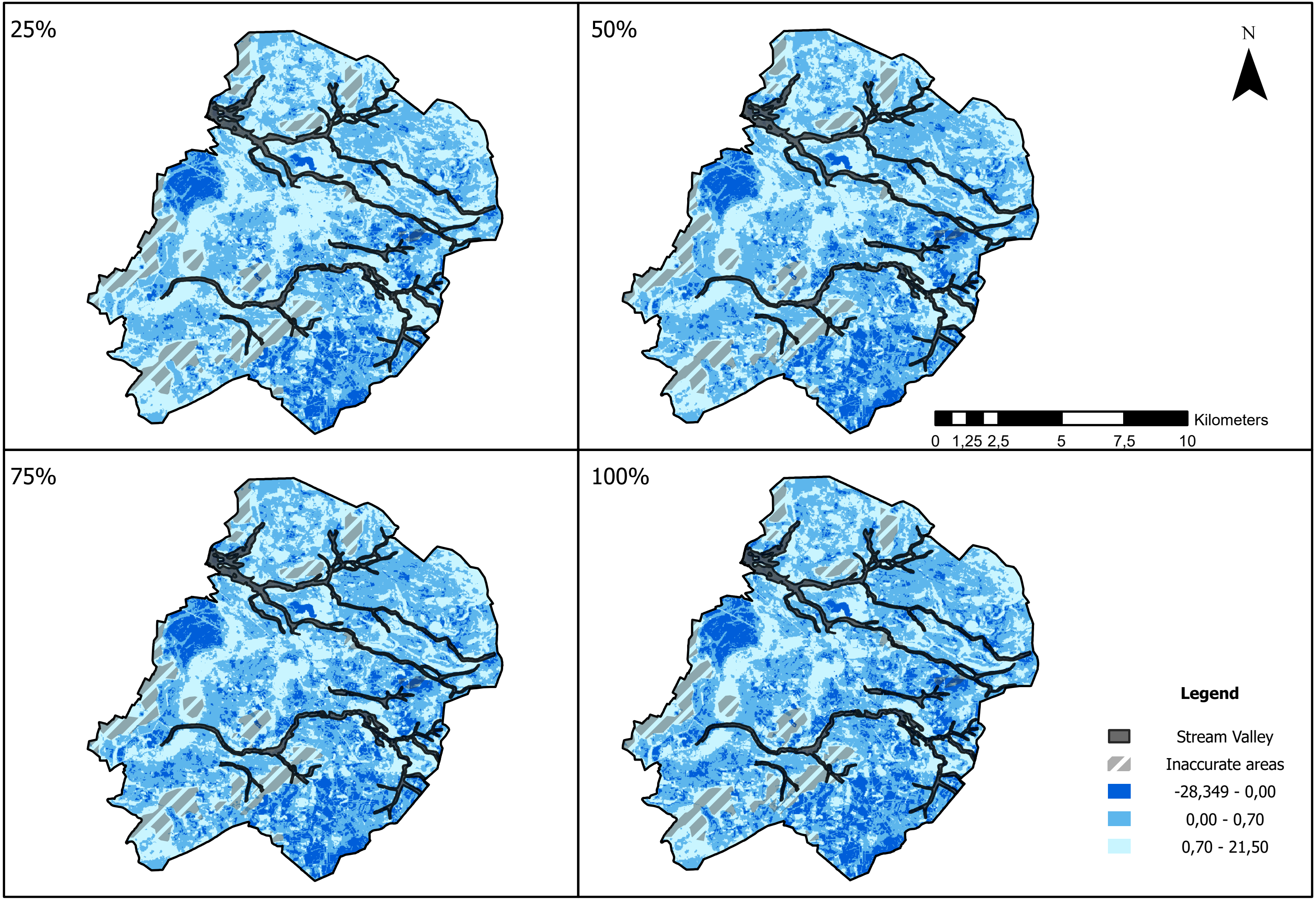
# APPENDICES

## APPENDIX A : LAND USE CATEGORIES

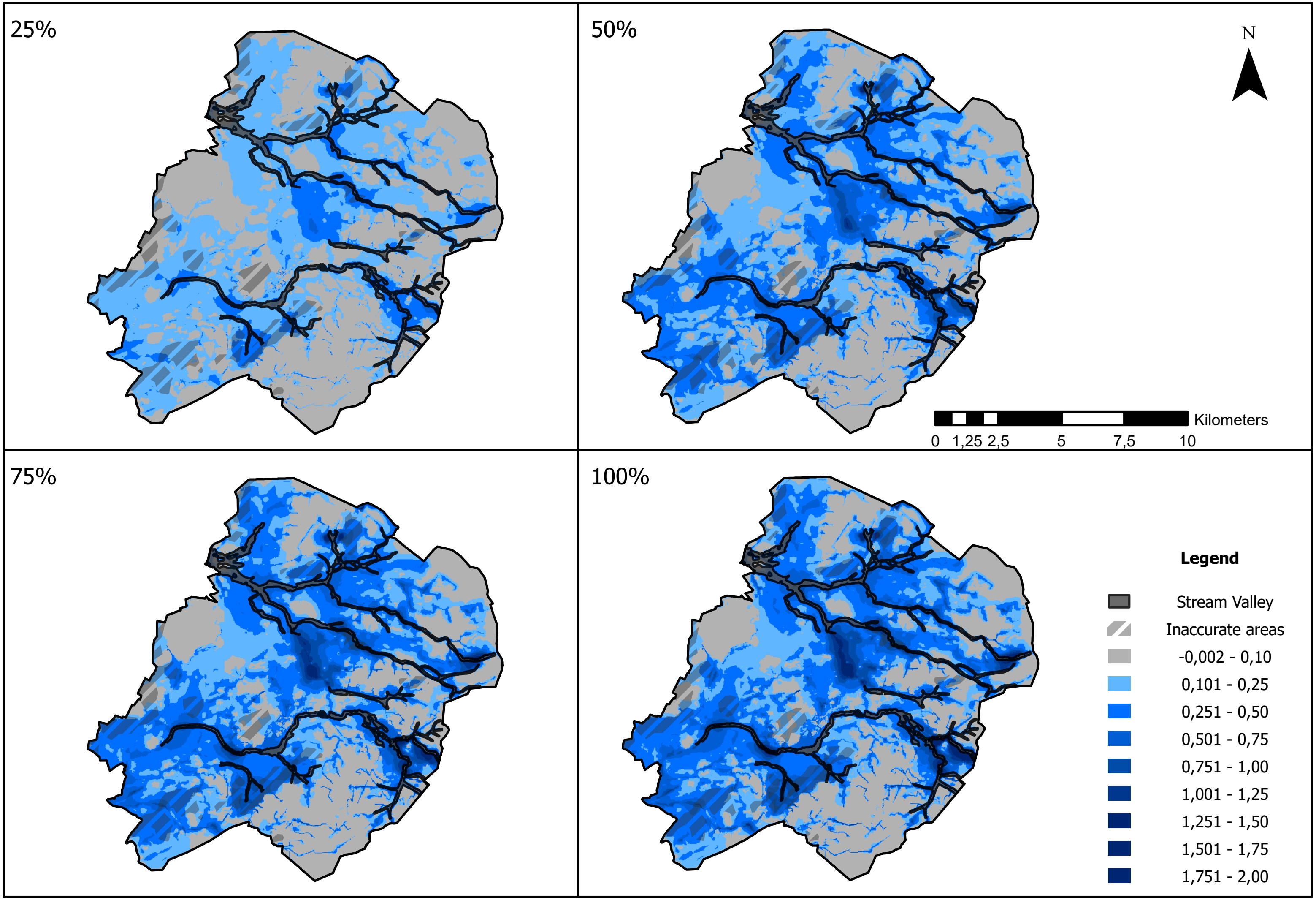
| Gridcode | LGN klasse | Hoofdklasse | opmerkingen |
|---|---|---|---|
| 1 | agrarisch gras | Landbouw | |
| 2 | mais | Landbouw | |
| 3 | aardappelen | Landbouw | |
| 4 | bieten | Landbouw | |
| 5 | granen | Landbouw | |
| 6 | overige landbouwgewassen | Landbouw | |
| 8 | glastuinbouw | Landbouw | |
| 9 | boomgaarden | Landbouw | |
| 10 | bloembollen | Landbouw | |
| 11 | loofbos | Natuur | |
| 12 | naaldbos | Natuur | |
| 16 | zoet water | | Oppervlakte water behoort niet tot een van deze categorieën |
| 18 | zout water | | Oppervlakte water behoort niet tot een van deze categorieën |
| 19 | bebouwing in secundair gebied | Stedelijk | |
| 20 | bos in primair bebouwd gebied | Stedelijk | |
| 22 | bos in secundair bebouwd gebied | Stedelijk | |
| 23 | gras in primair bebouwd gebied | Stedelijk | |
| 26 | bebouwing in buitengebied | Stedelijk | |
| 27 | overig grondgebruik in buitengebied | Stedelijk | |
| 28 | gras in secundair bebouwd gebied | Stedelijk | |
| 35 | open stuifzand en/of rivierzand | Natuur | |
| 36 | heide | Natuur | |
| 37 | matig vergraste heide | Natuur | |
| 38 | sterk vergraste heide | Natuur | |
| 39 | hoogveen | Natuur | |
| 40 | bos in hoogveengebied | Natuur | |
| 41 | overige moeras vegetatie | Natuur | |
| 42 | rietvegetatie | Natuur | |
| 43 | bos in moerasgebied | Natuur | |
| 45 | natuurlijk beheerde agrarische gebieden | Landbouw | Dit zijn natuurlijke gebieden, maar aangezien het wel beheert wordt op een agrarische wijze, classificeer ik het als landbouw |
| 47 | overig gras | Natuur | Dit is omringt door natuurgebieden (zoals naaldbos) dus ik neem aan dat dit nog onderdeel is van het bos |
| 61 | boomkwekerijen | Landbouw | |
| 62 | fruitkwekerijen | Landbouw | |
| 251 | hoofdinfrastructuur en spoorbaanlichamen | | Infrastructuur behoort niet tot een van deze categorieën |
| 252 | halfverharde wegen, infrastructuur langzaam verkeer en overige infrastructuur | | Infrastructuur behoort niet tot een van deze categorieën |
| 253 | smalle wegen | | Infrastructuur behoort niet tot een van deze categorieën |
| 321 | struikvegetatie in hoogveengebied (laag) | Natuur | |
| 322 | struikvegetatie in moerasgebied (laag) | Natuur | |
| 323 | overige struikvegetatie (laag) | Natuur | |
| 331 | struikvegetatie in hoogveengebied (hoog) | Natuur | |
| 332 | struikvegetatie in moerasgebied (hoog) | Natuur | |
| 333 | overig struikvegetatie (hoog) | Natuur | |

## Appendix B : Spatial distribution of the reprofiling measures

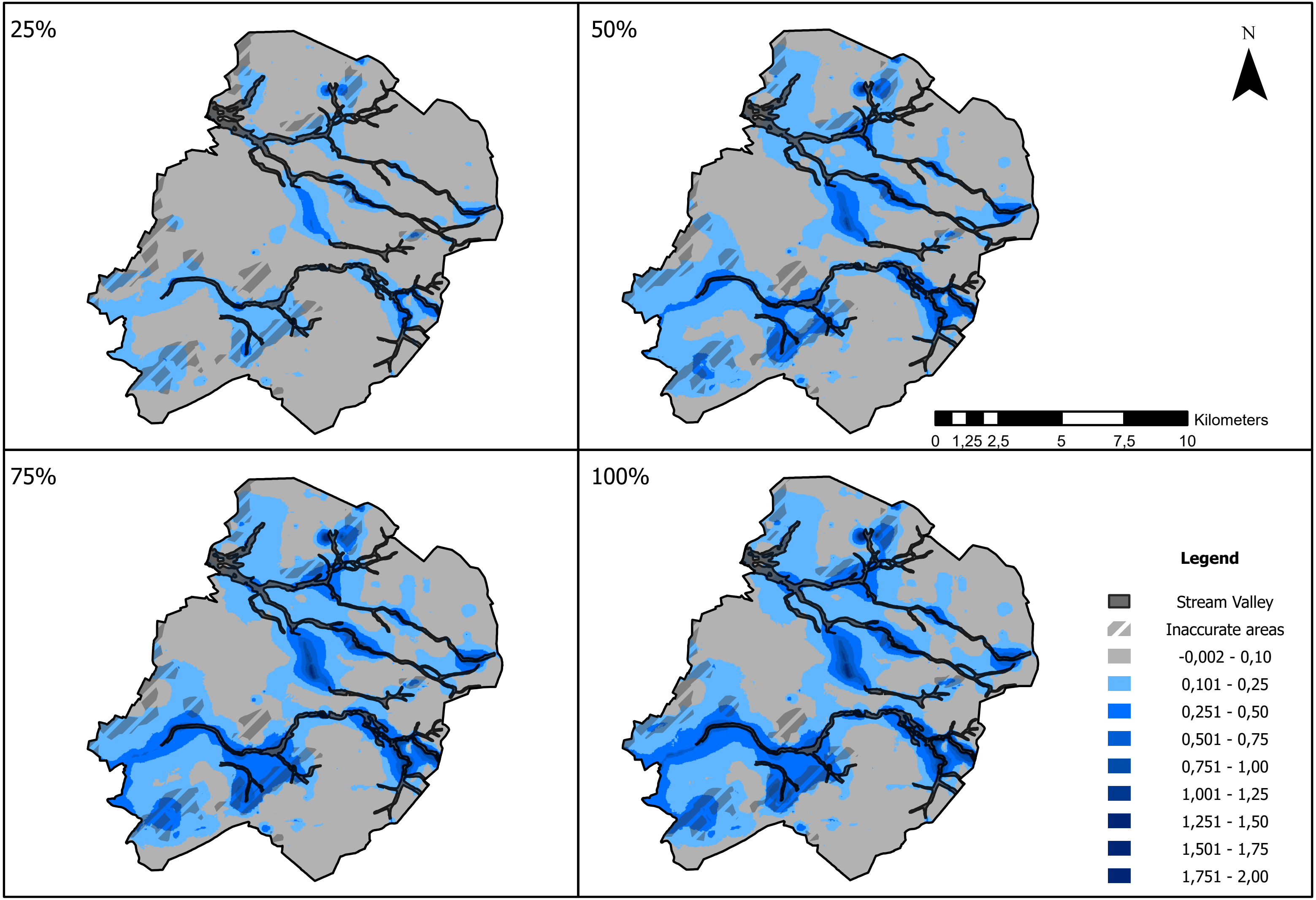
*Reprofiling primary watercourses - increase in HG3 with respect to the surface level [m] in 2017*

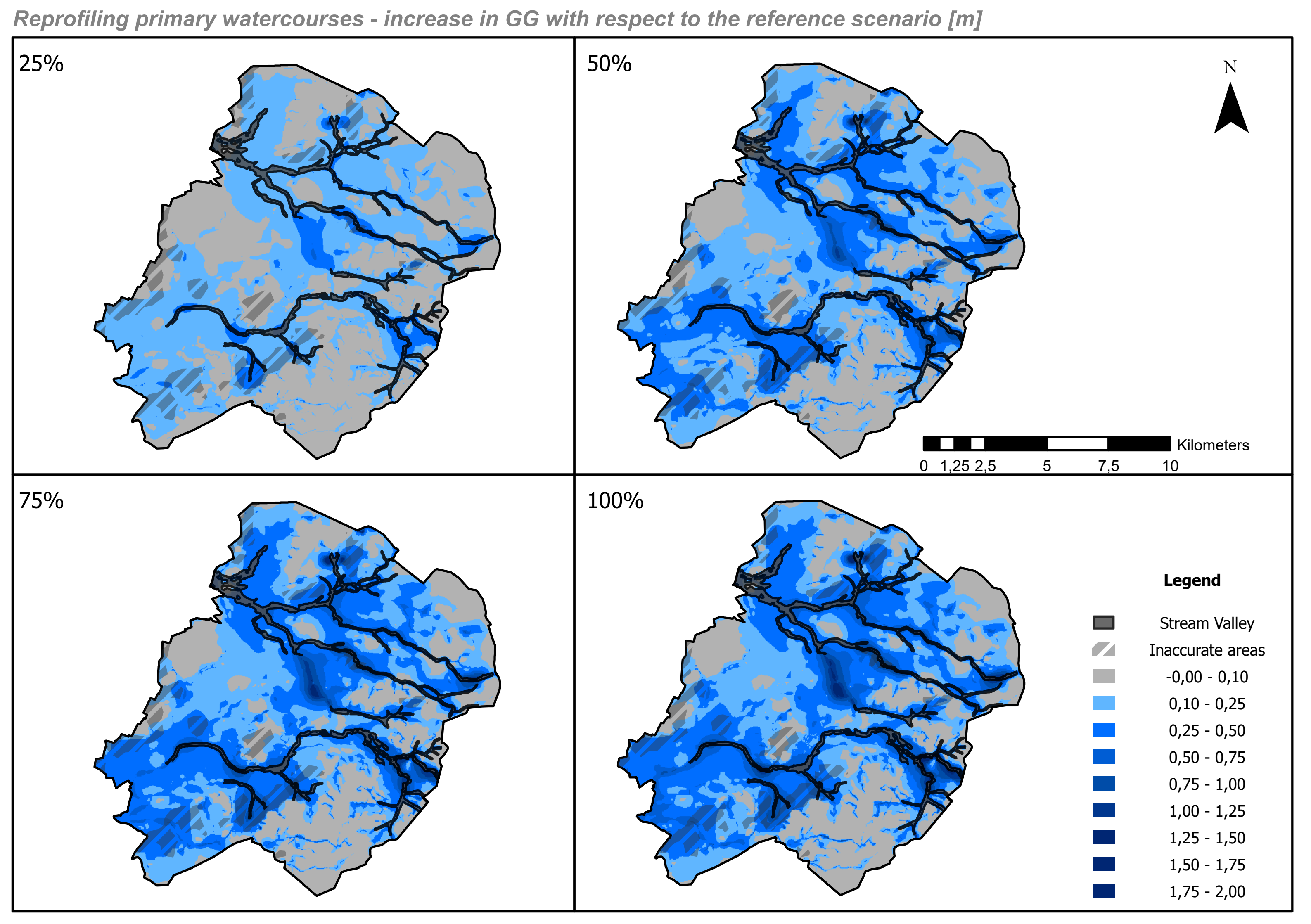


Reprofiling primary watercourses - increase in HG3 with respect to the reference scenario [m] in 2017

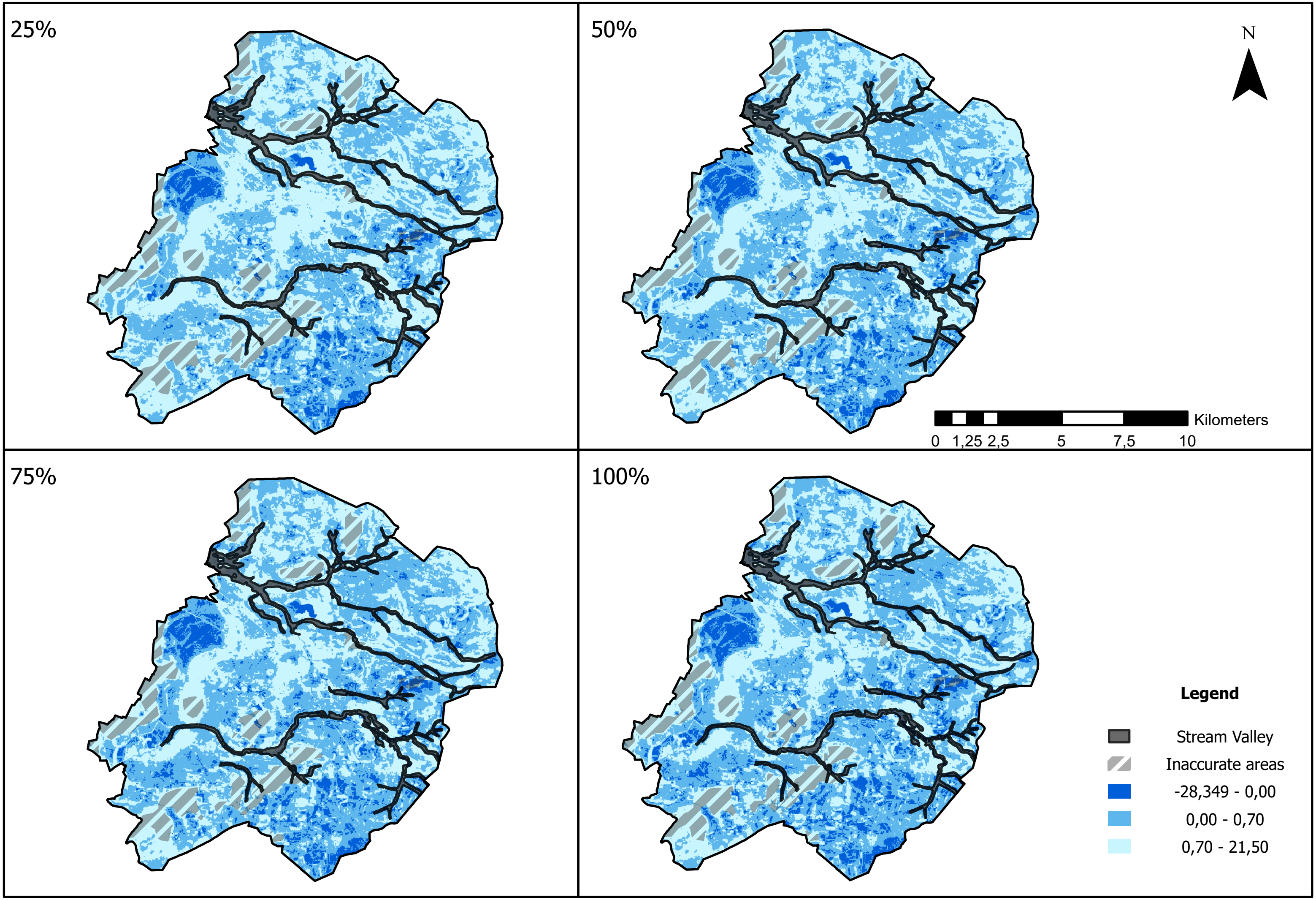


*Reprofiling primary watercourses - increase in LG3 with respect to the reference scenario [m] in 2018*

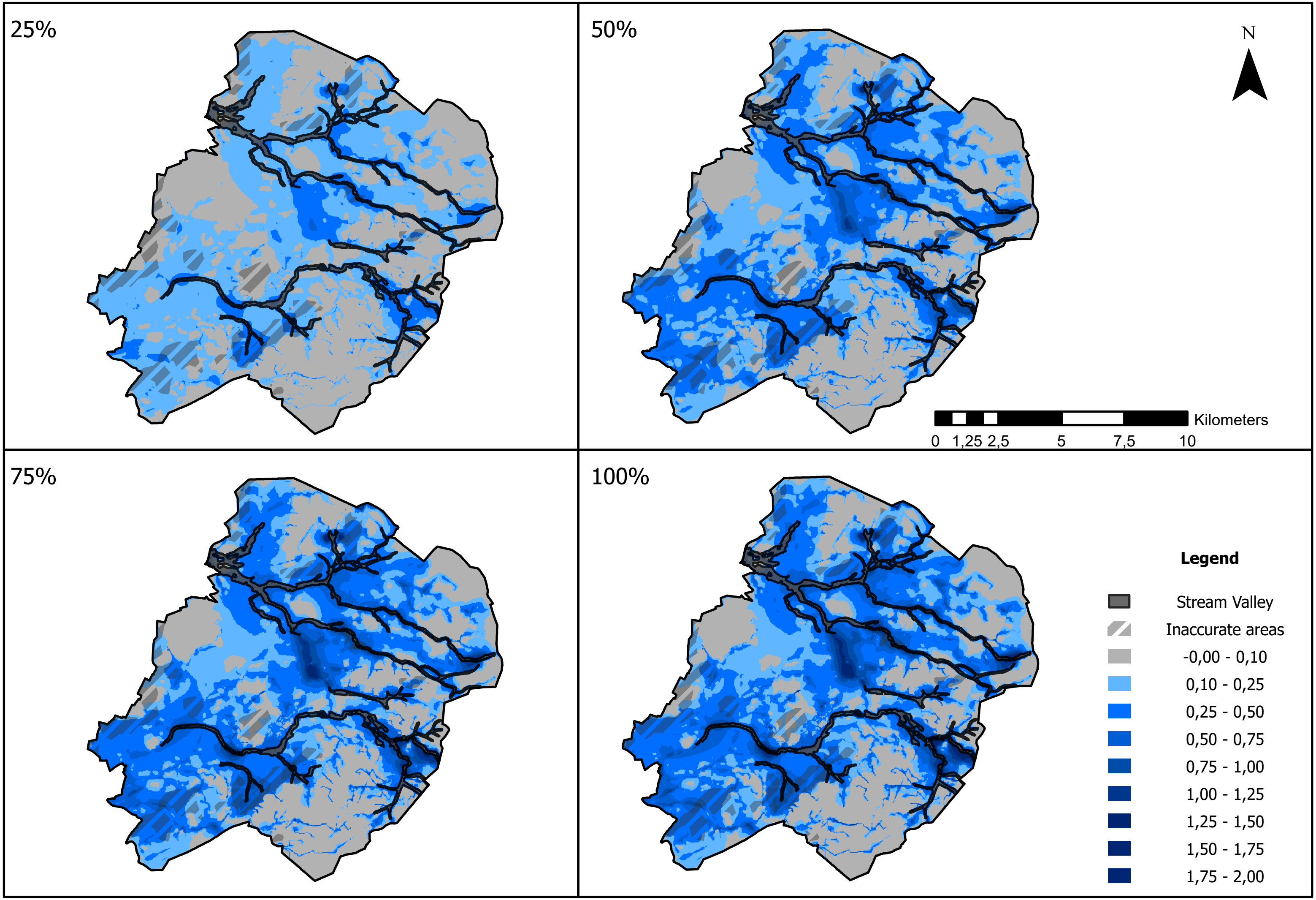



Reprofiling primary watercourses - increase in GG with respect to the reference scenario [m]
25%
50%
75%
100%
N
0
1,25
2,5
5
7,5
10
Kilometers
Legend
Stream Valley
Inaccurate areas
-0,00 - 0,10
0,10 - 0,25
0,25 - 0,50
0,50 - 0,75
0,75 - 1,00
1,00 - 1,25
1,25 - 1,50
1,50 - 1,75
1,75 - 2,00

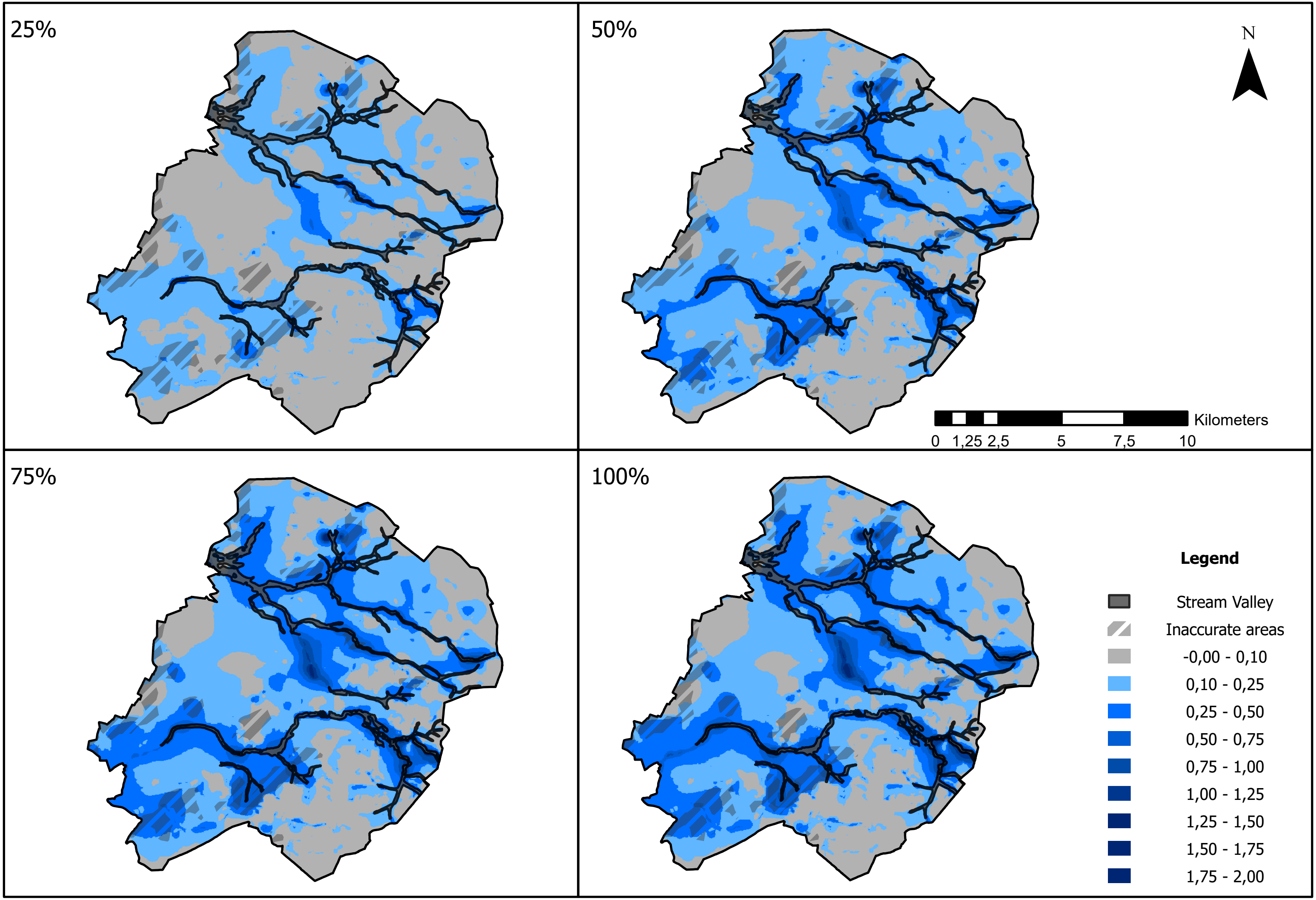
Reprofiling primary watercourses - increase in GHG with respect to the surface level [m]



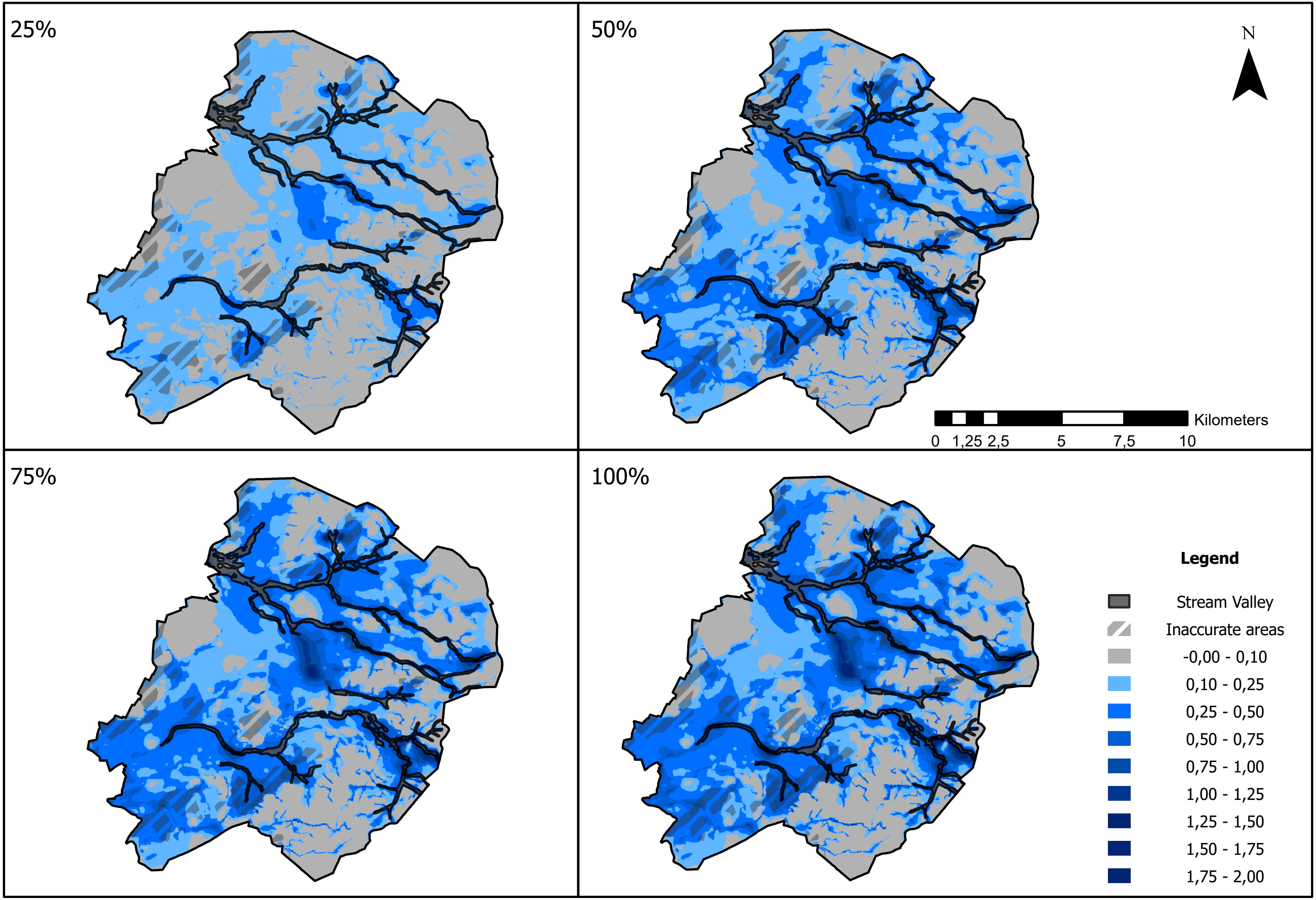
***Reprofiling primary watercourses - increase in GHG with respect to the reference scenario [m]***



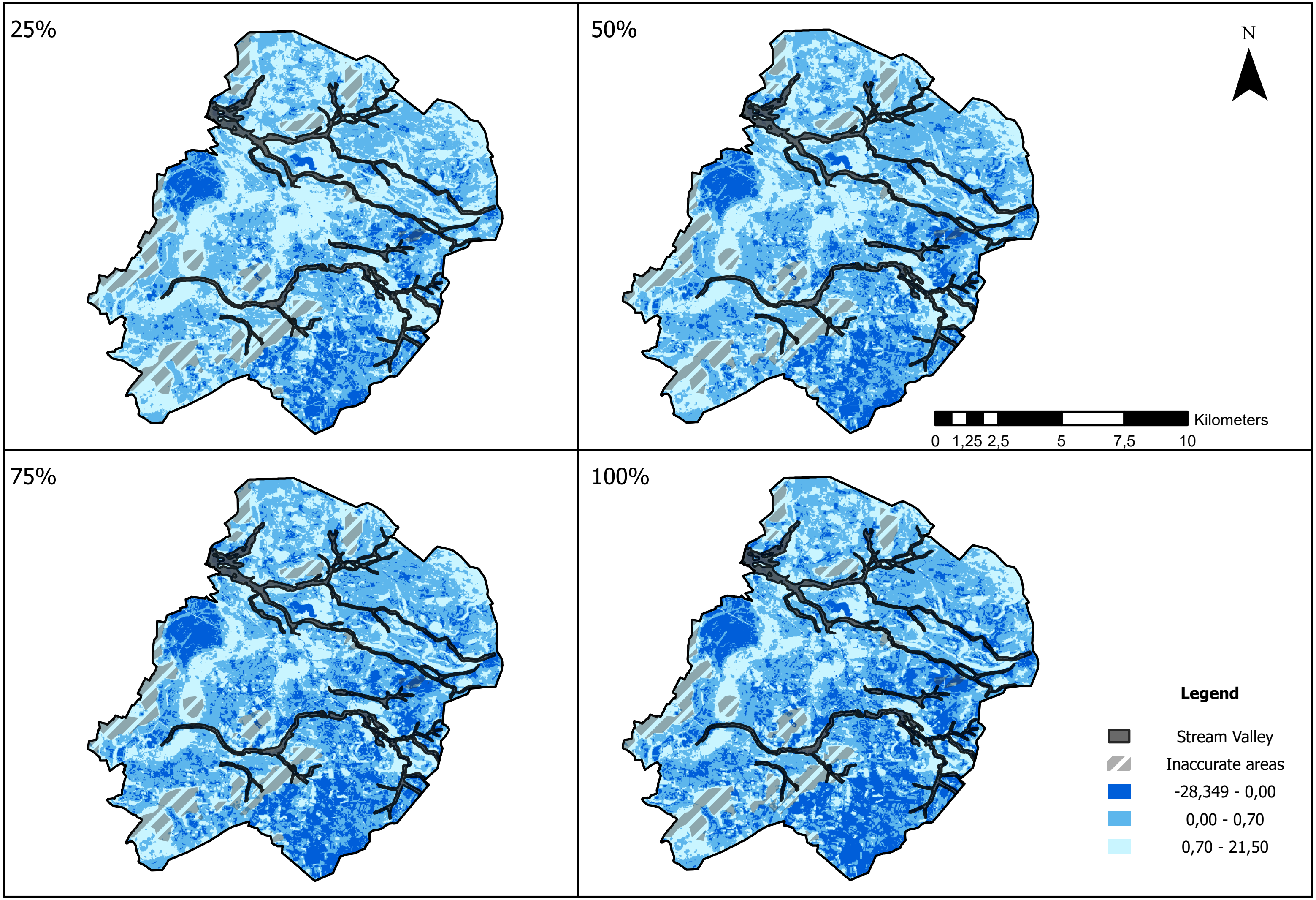
Reprofiling primary watercourses - increase in GLG with respect to the reference scenario [m]



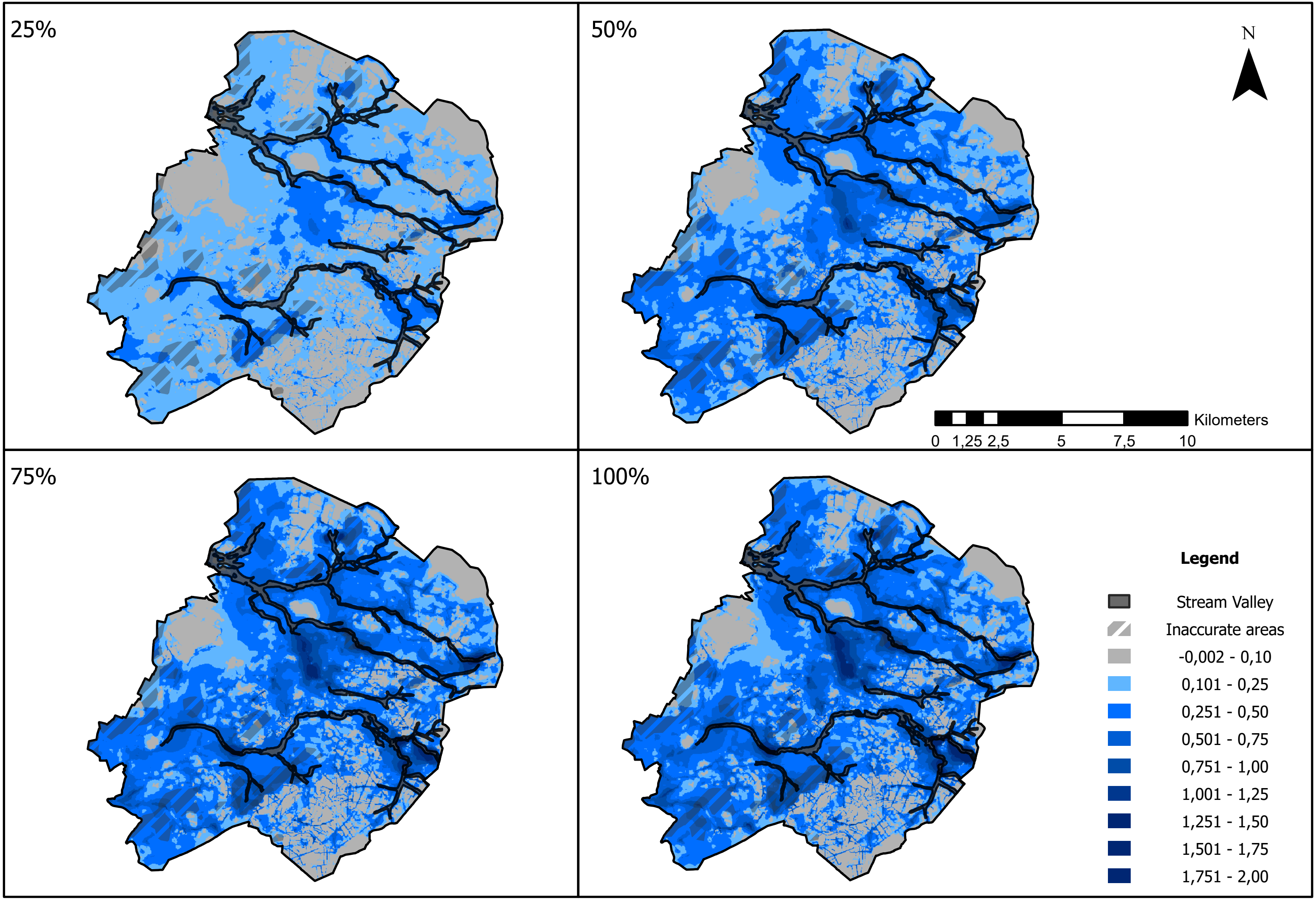
Reprofiling primary watercourses - increase in GVG with respect to the reference scenario [m]



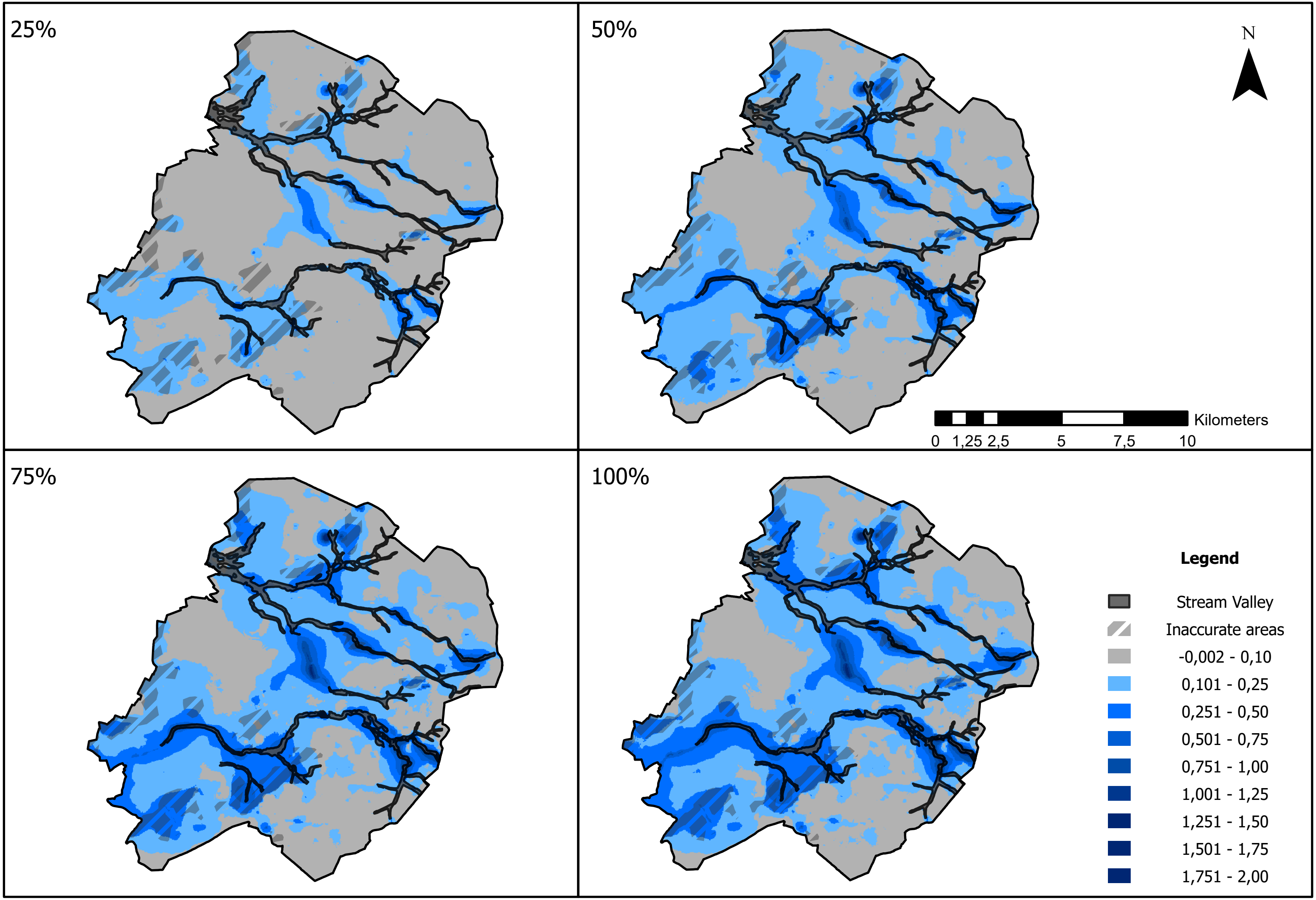
*Reprofiling primary and secondary watercourses - increase in HG3 with respect to the surface level [m] in 2017*

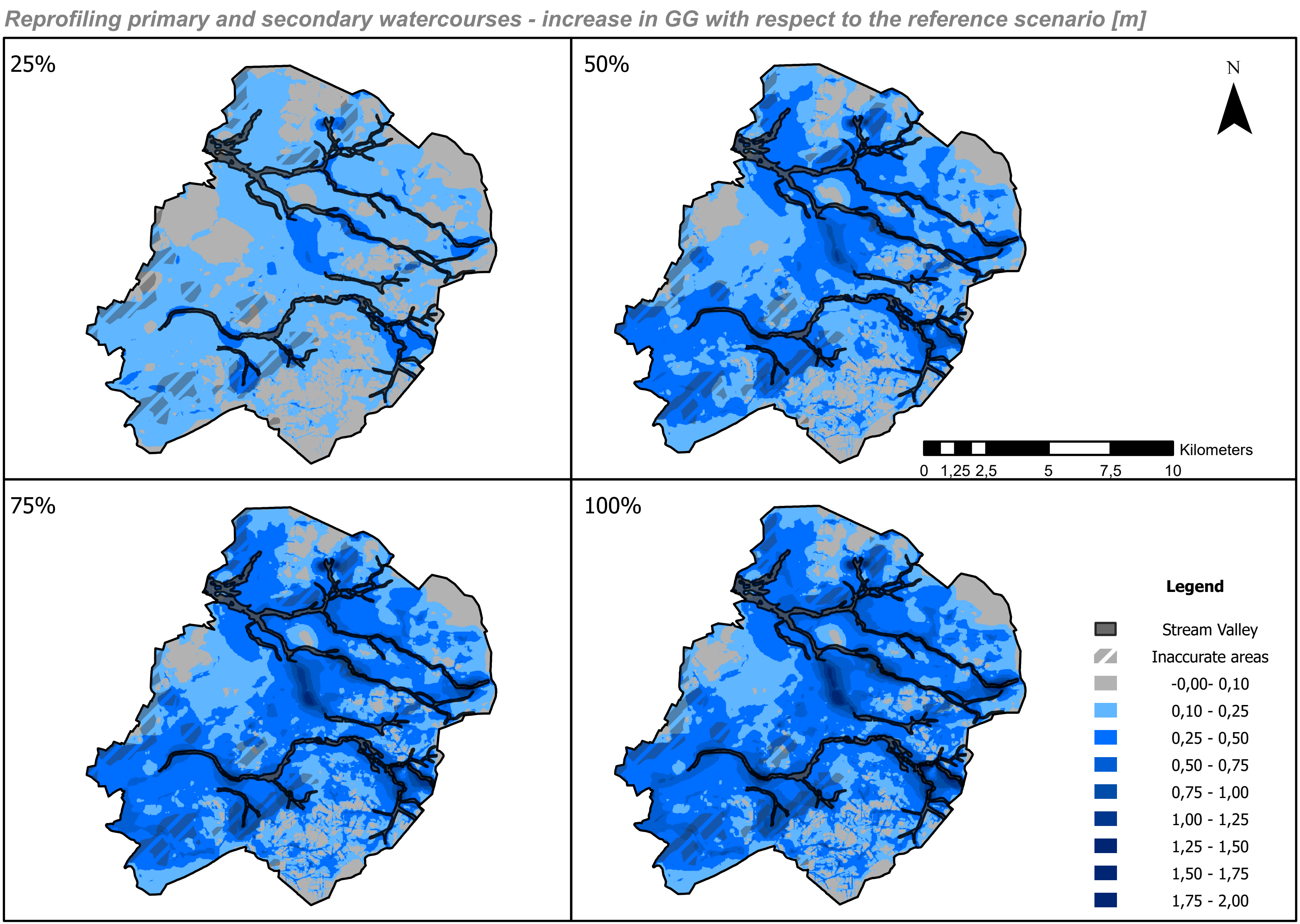


***Reprofiling primary and secondary watercourses - increase in HG3 with respect to the reference scenario [m] in 2017***

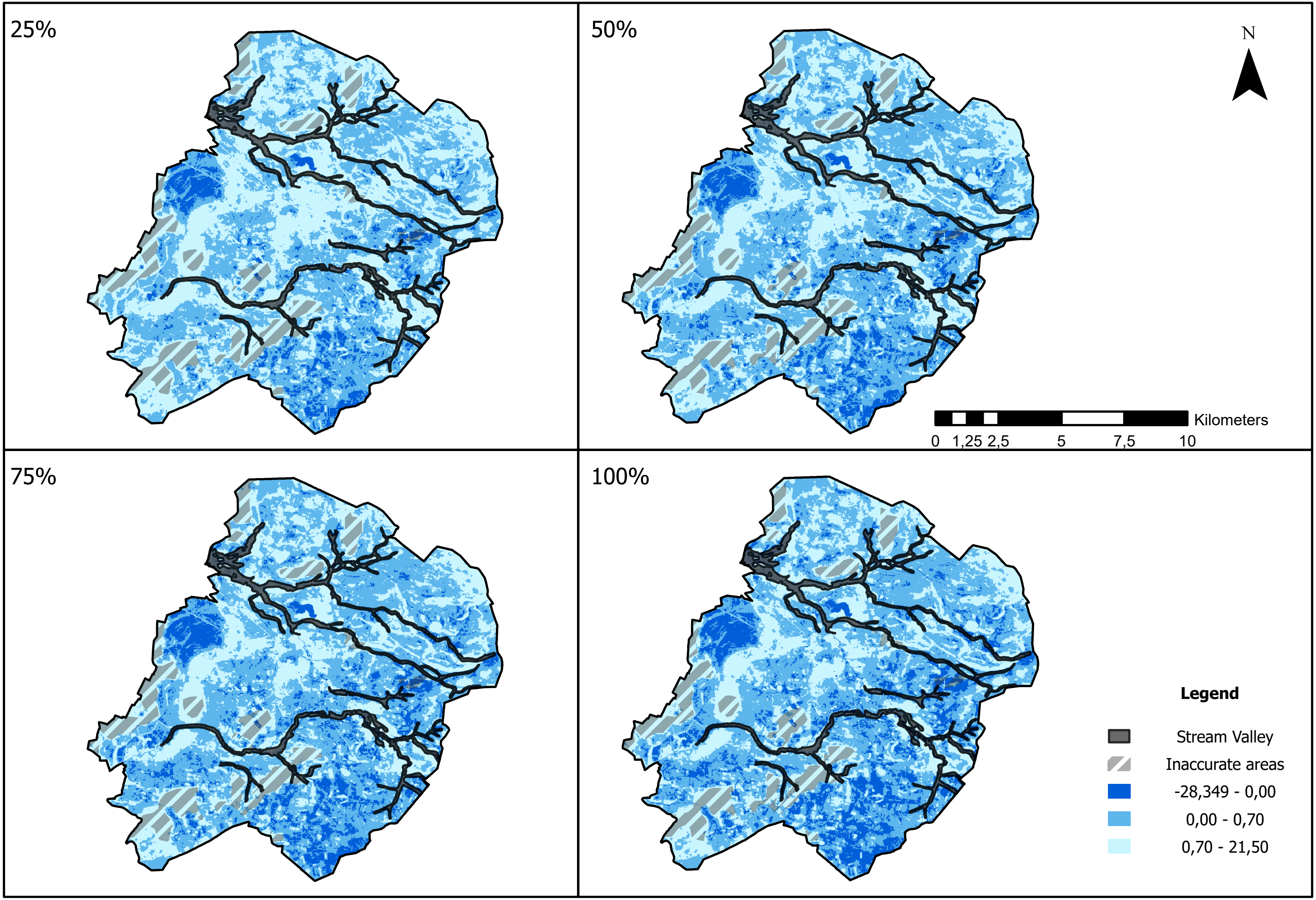


*Reprofiling primary and secondary watercourses - increase in LG3 with respect to the reference scenario [m] in 2018*

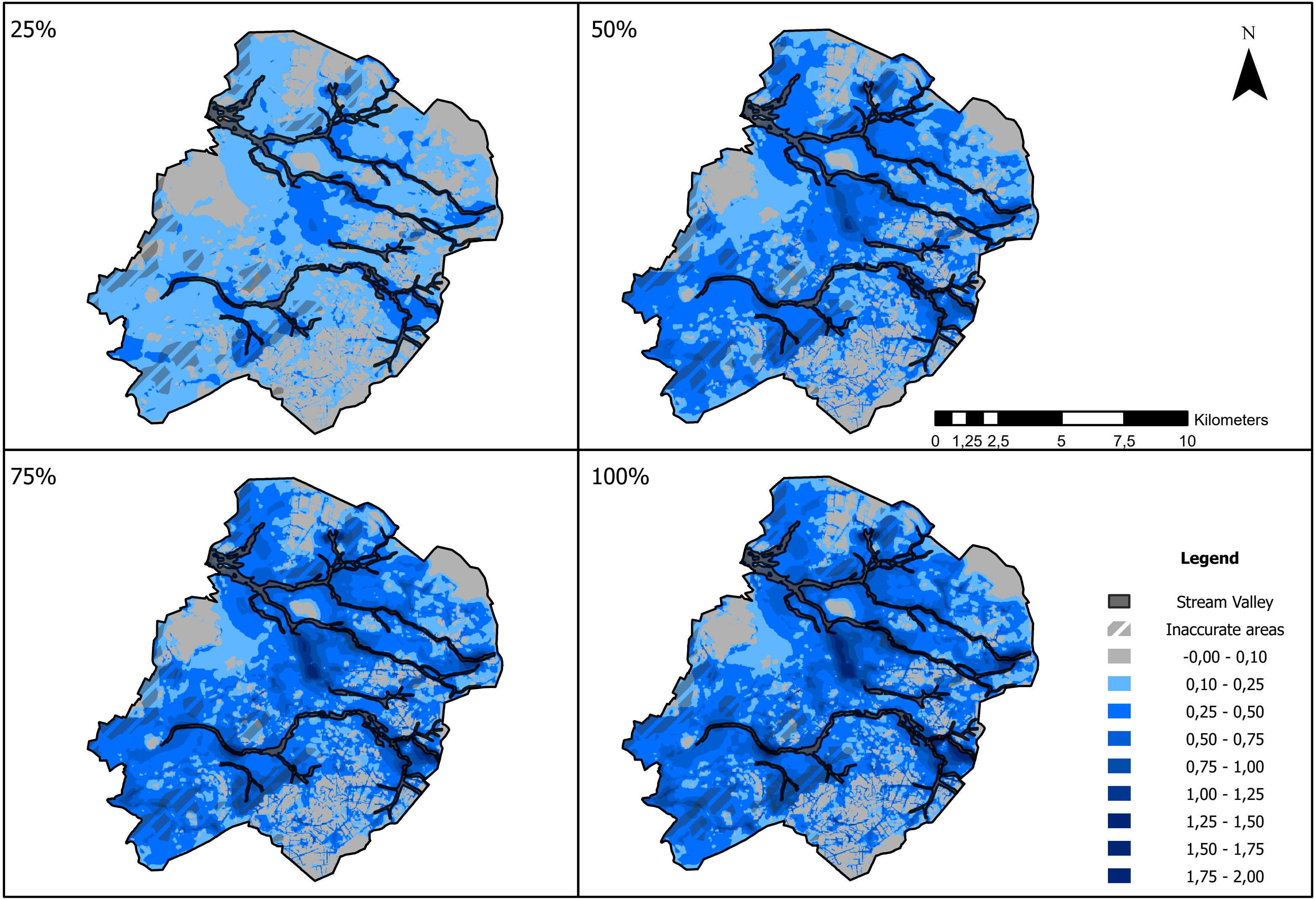



Reprofiling primary and secondary watercourses - increase in GG with respect to the reference scenario [m]
25%
50%
75%
100%
N
0
1,25
2,5
5
7,5
10
Kilometers
Legend
Stream Valley
Inaccurate areas
-0,00- 0,10
0,10 - 0,25
0,25 - 0,50
0,50 - 0,75
0,75 - 1,00
1,00 - 1,25
1,25 - 1,50
1,50 - 1,75
1,75 - 2,00

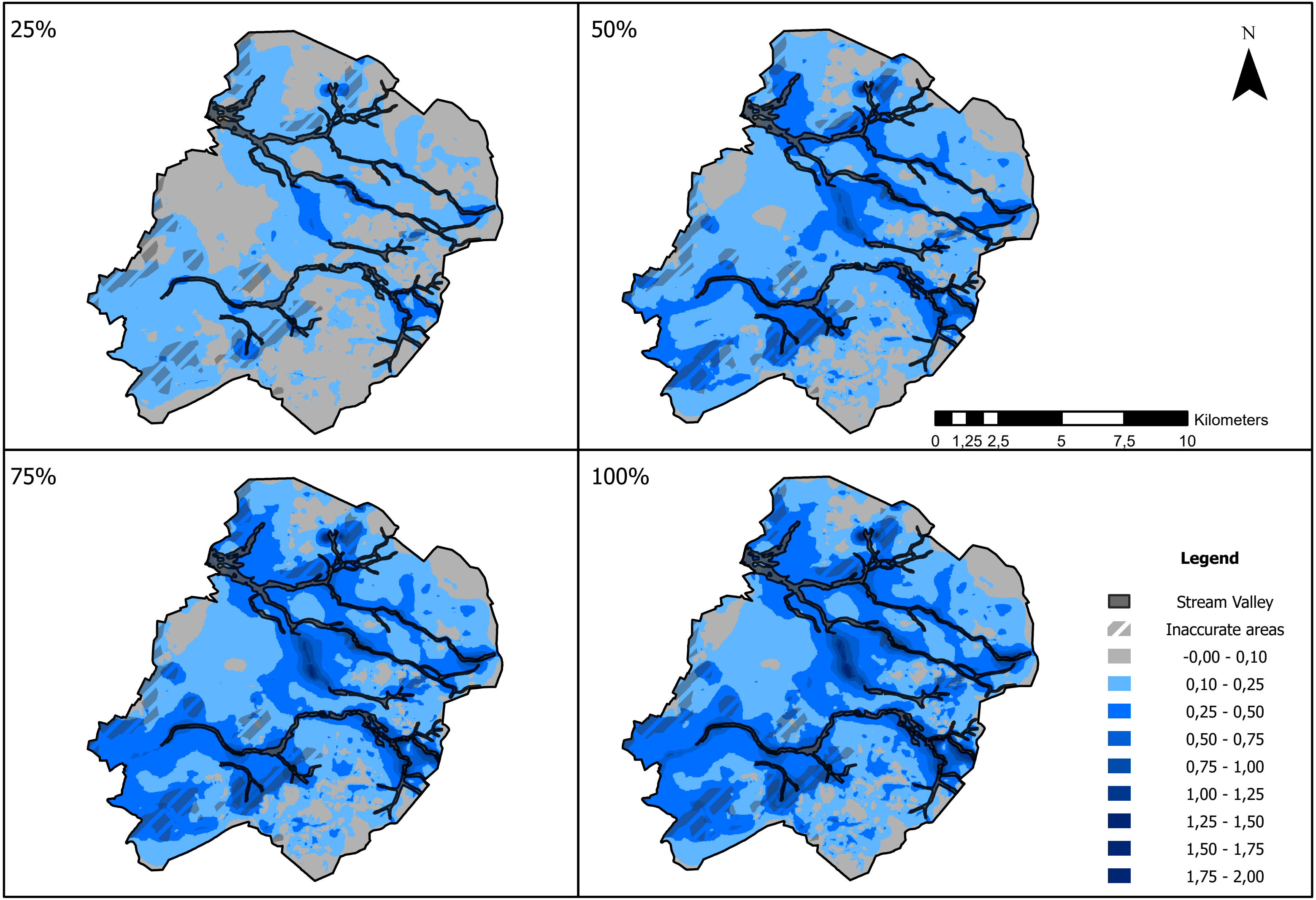
*Reprofiling primary and secondary watercourses - increase in GHG with respect to the surface level [m]*



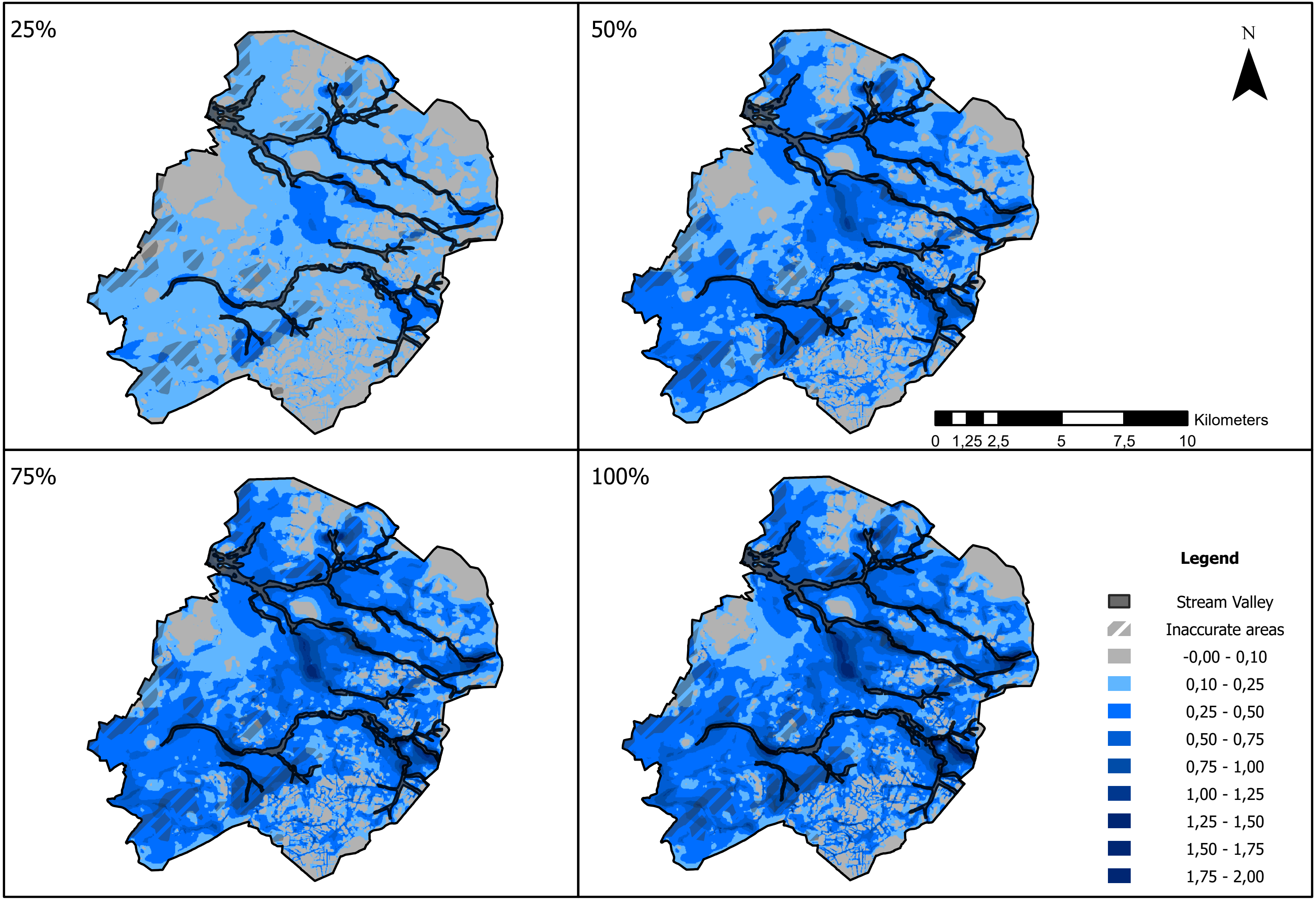
*Reprofiling primary and secondary watercourses - increase in GHG with respect to the reference scenario [m]*



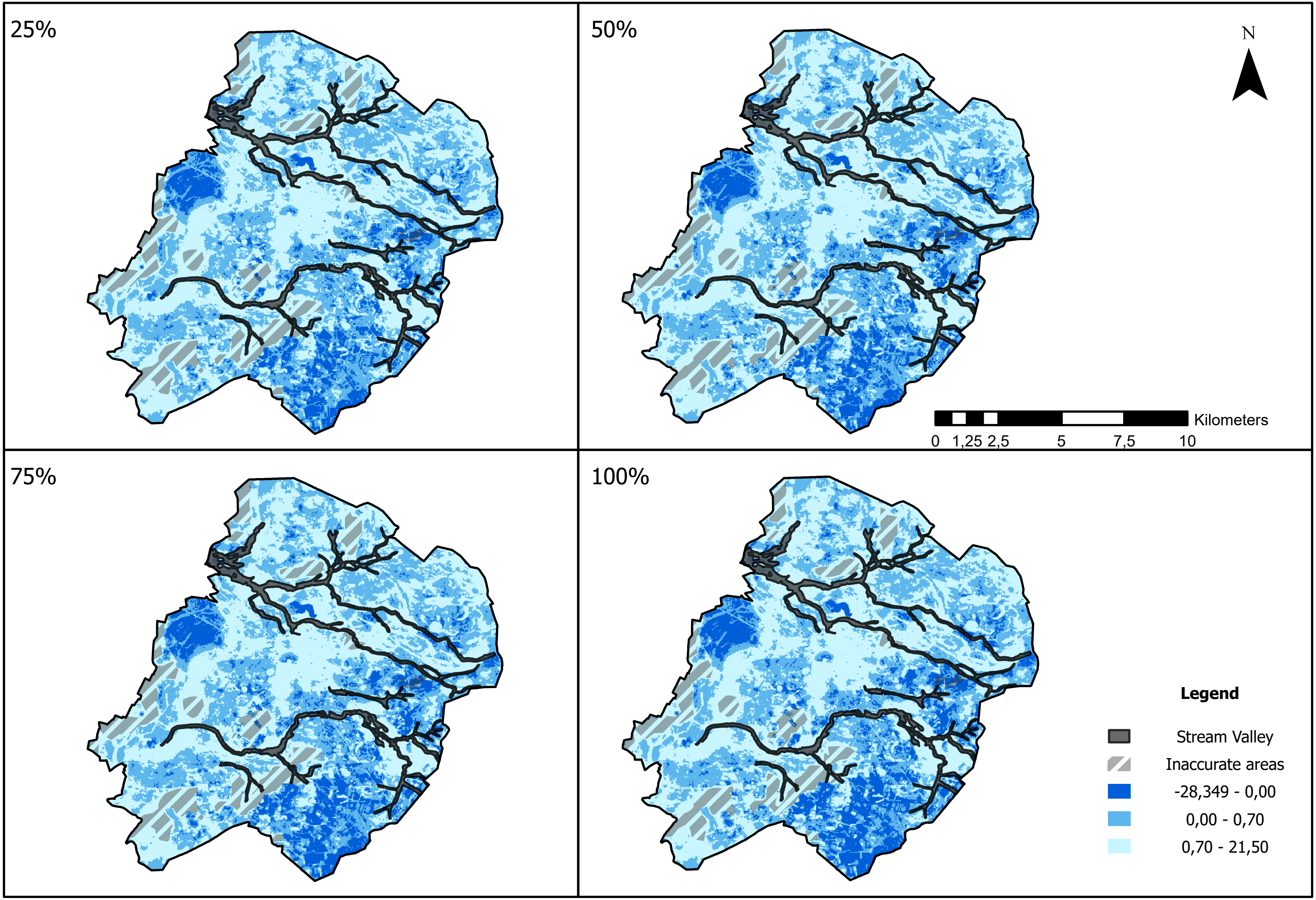
Reprofiling primary and secondary watercourses - increase in GLG with respect to the reference scenario [m]



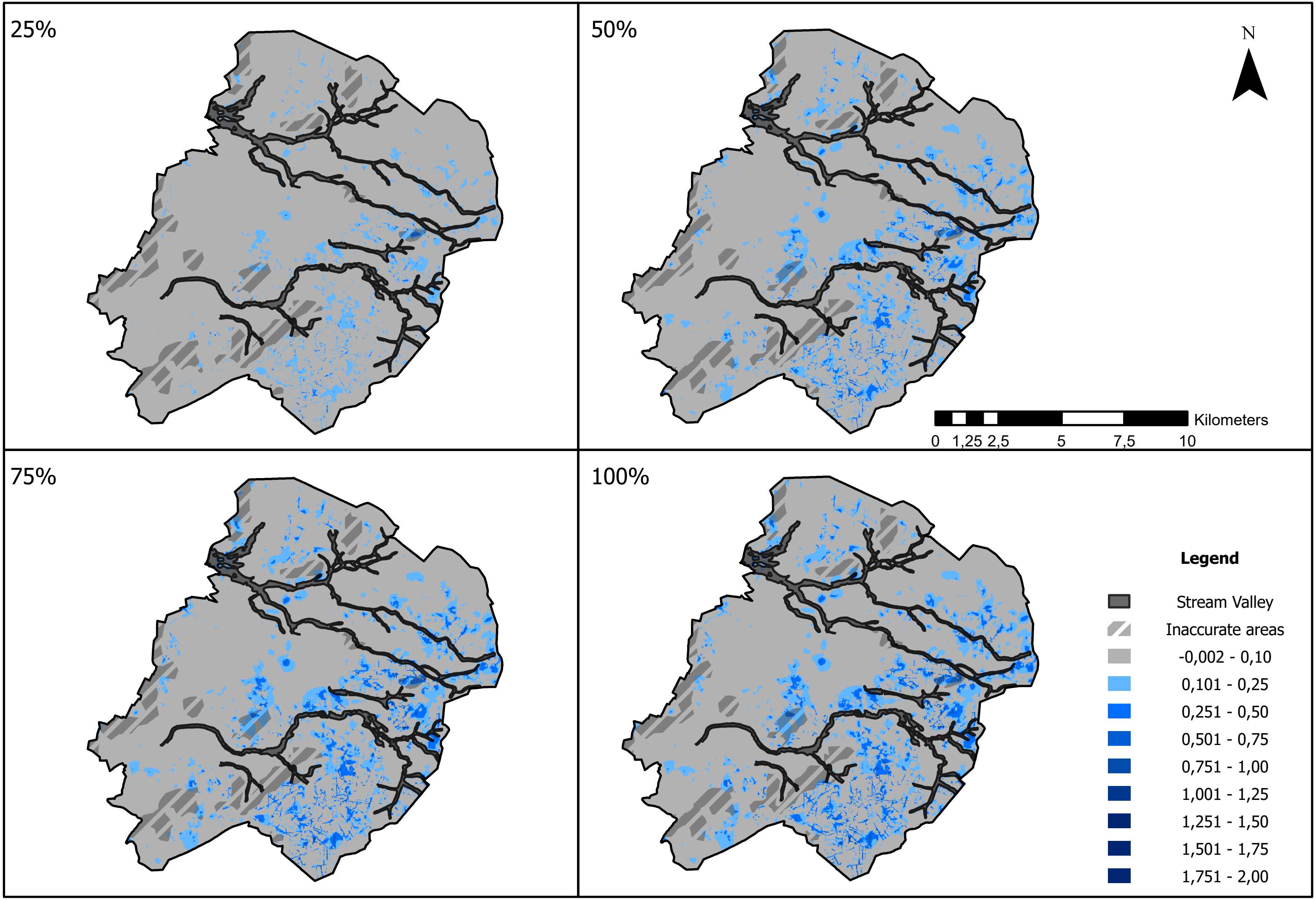
*Reprofiling primary and secondary watercourses - increase in GVG with respect to the reference scenario [m]*



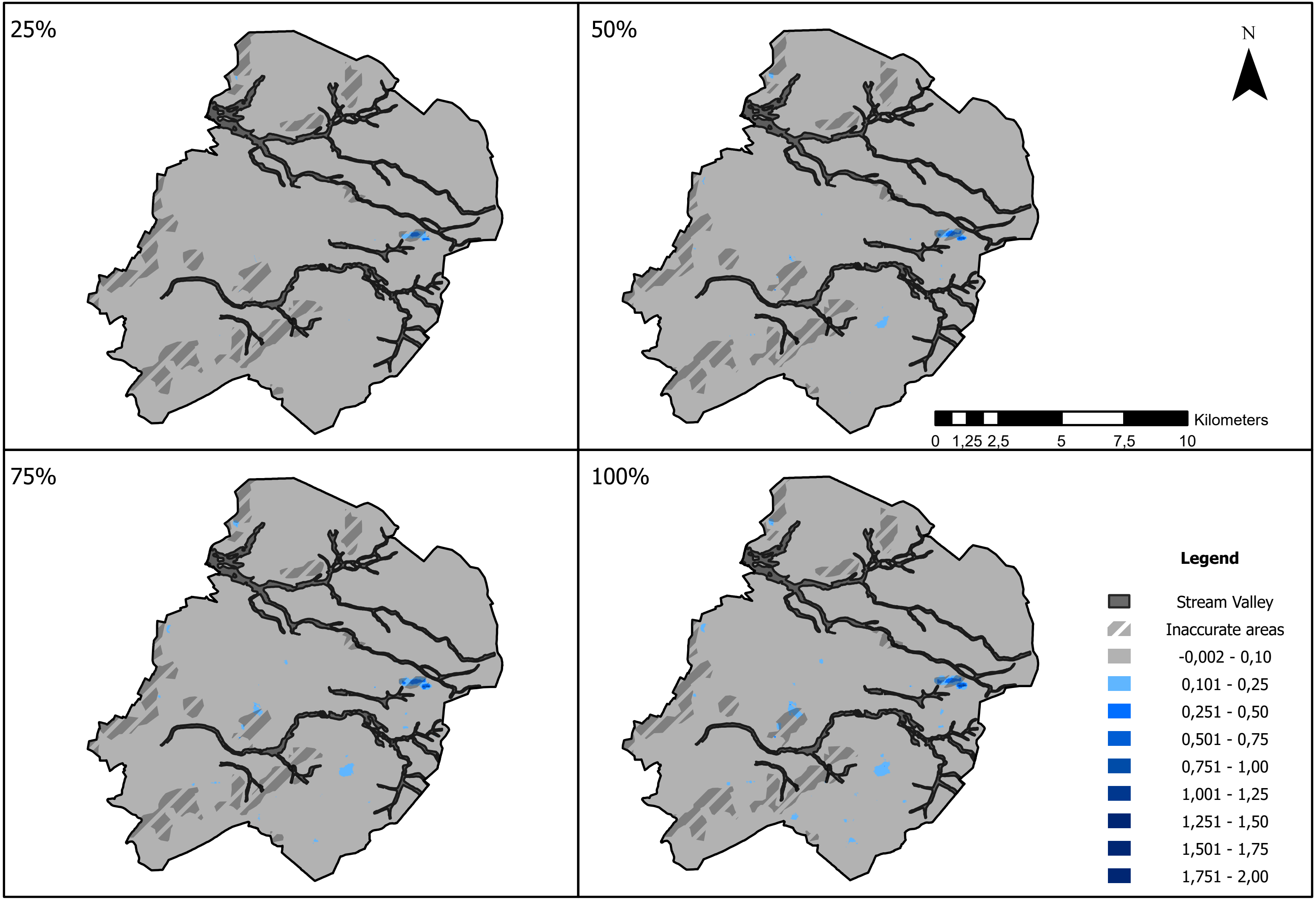
Reprofiling secondary watercourses - increase in HG3 with respect to the surface level [m] in 2017



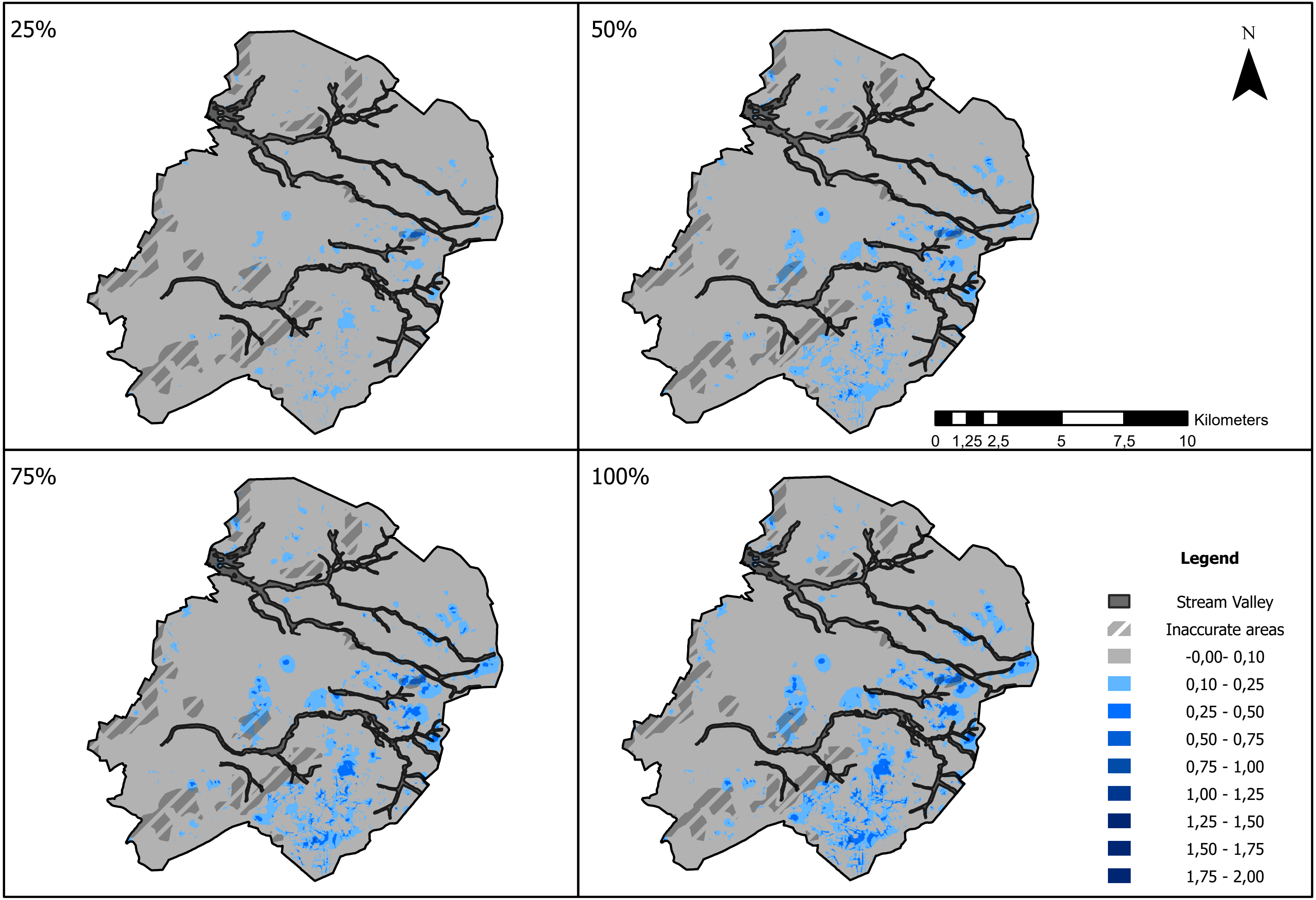
**Reprofiling primary watercourses - increase in HG3 with respect to the reference scenario [m] in 2017**



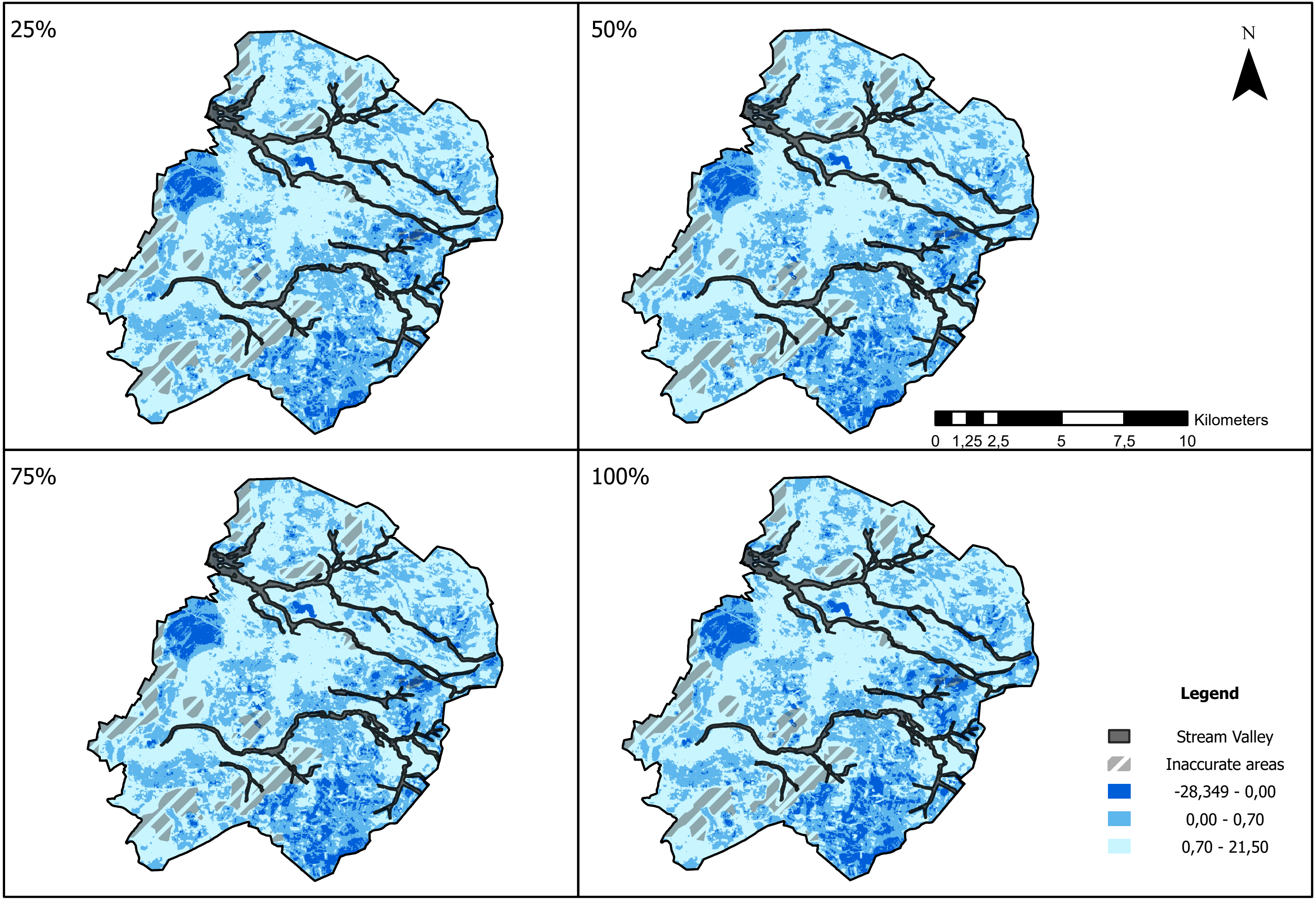
*Reprofiling secondary watercourses - increase in LG3 with respect to the reference scenario [m] in 2018*

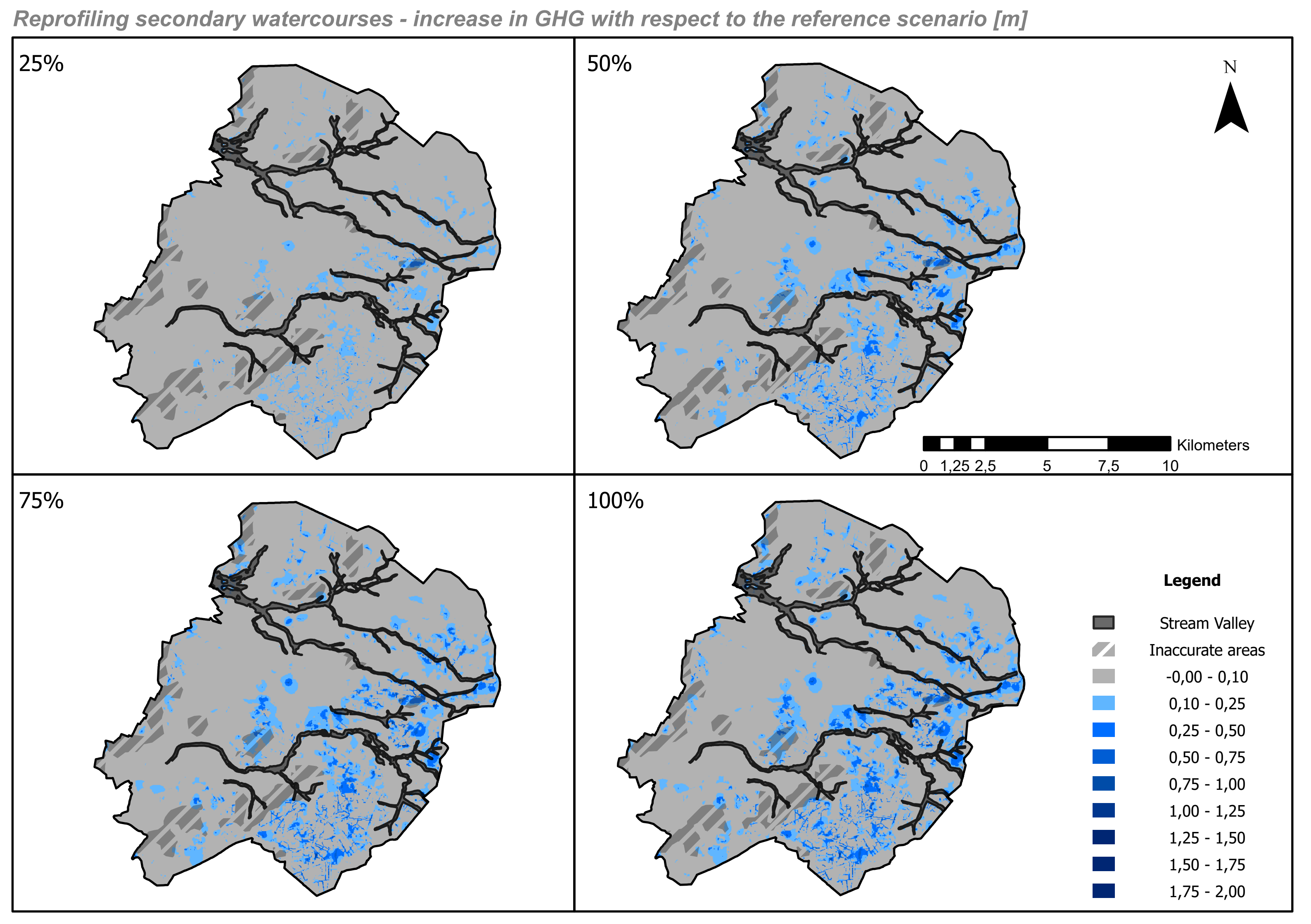


*Reprofiling secondary watercourses - increase in GG with respect to the reference scenario [m]*

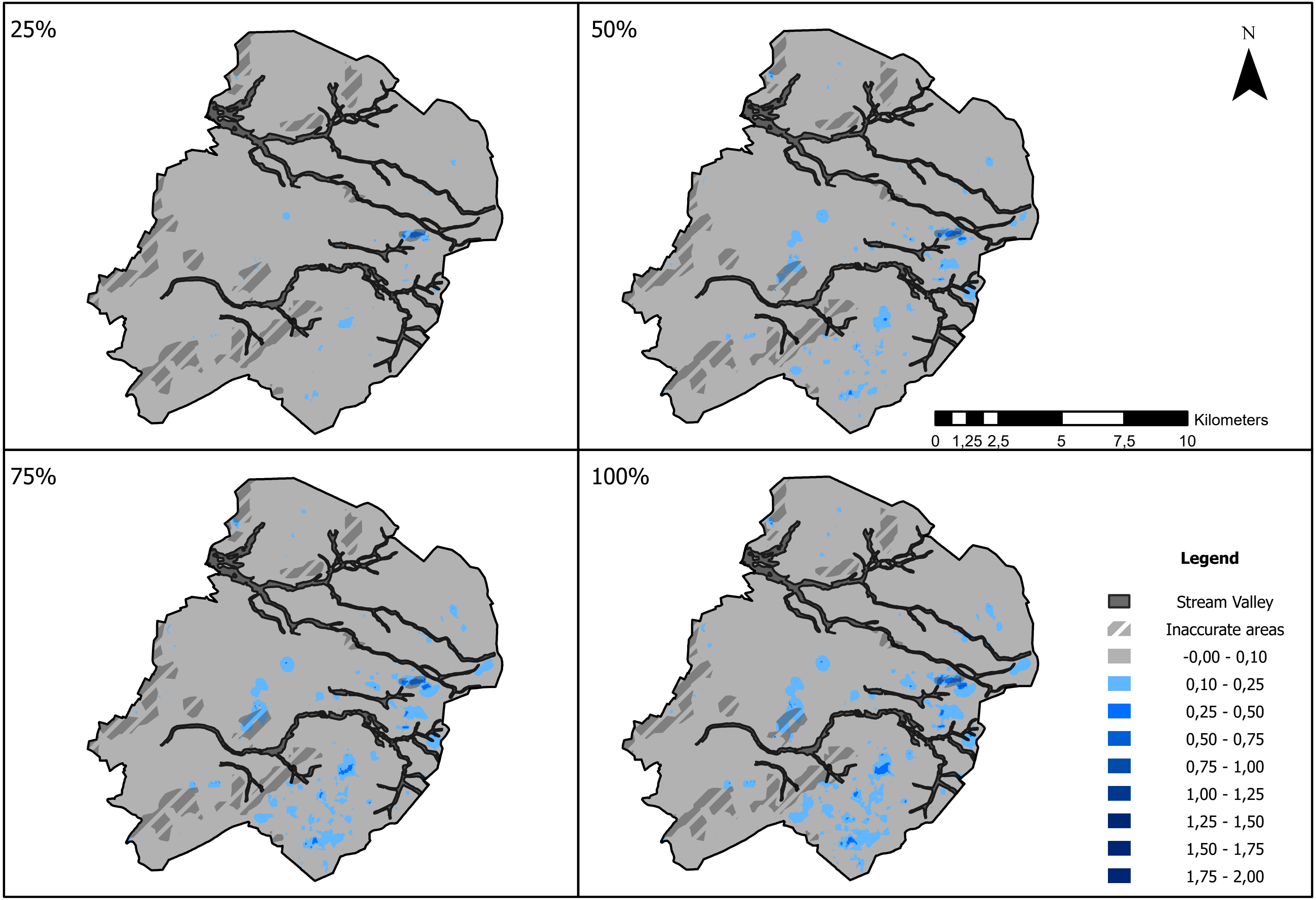


*Reprofiling secondary watercourses - increase in GHG with respect to the surface level [m]*

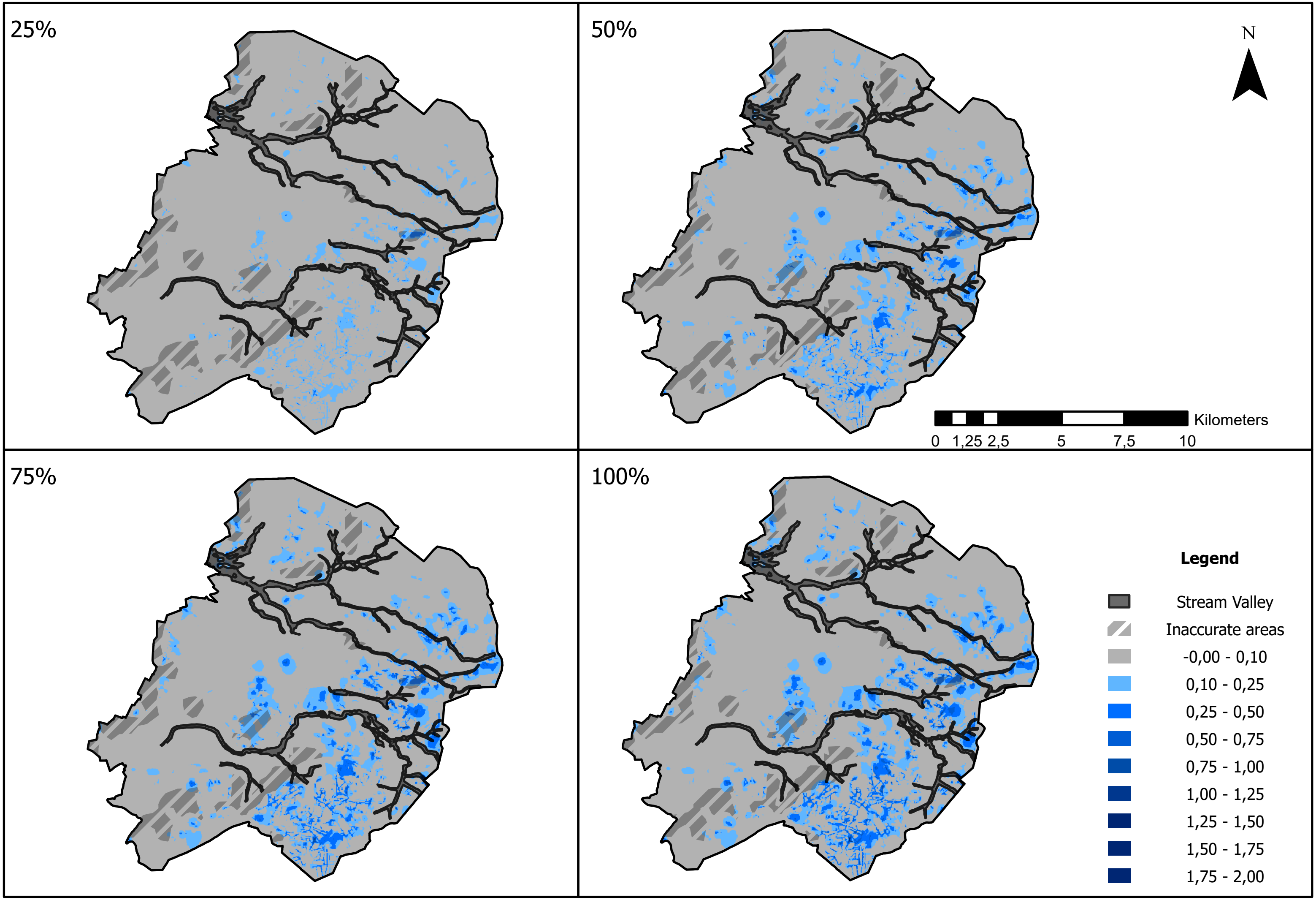



Reprofiling secondary watercourses - increase in GHG with respect to the reference scenario [m]
25%
50%
75%
100%
N
Kilometers
0
1,25
2,5
5
7,5
10
Legend
Stream Valley
Inaccurate areas
-0,00 - 0,10
0,10 - 0,25
0,25 - 0,50
0,50 - 0,75
0,75 - 1,00
1,00 - 1,25
1,25 - 1,50
1,50 - 1,75
1,75 - 2,00

*Reprofiling secondary watercourses - increase in GLG with respect to the reference scenario [m]*

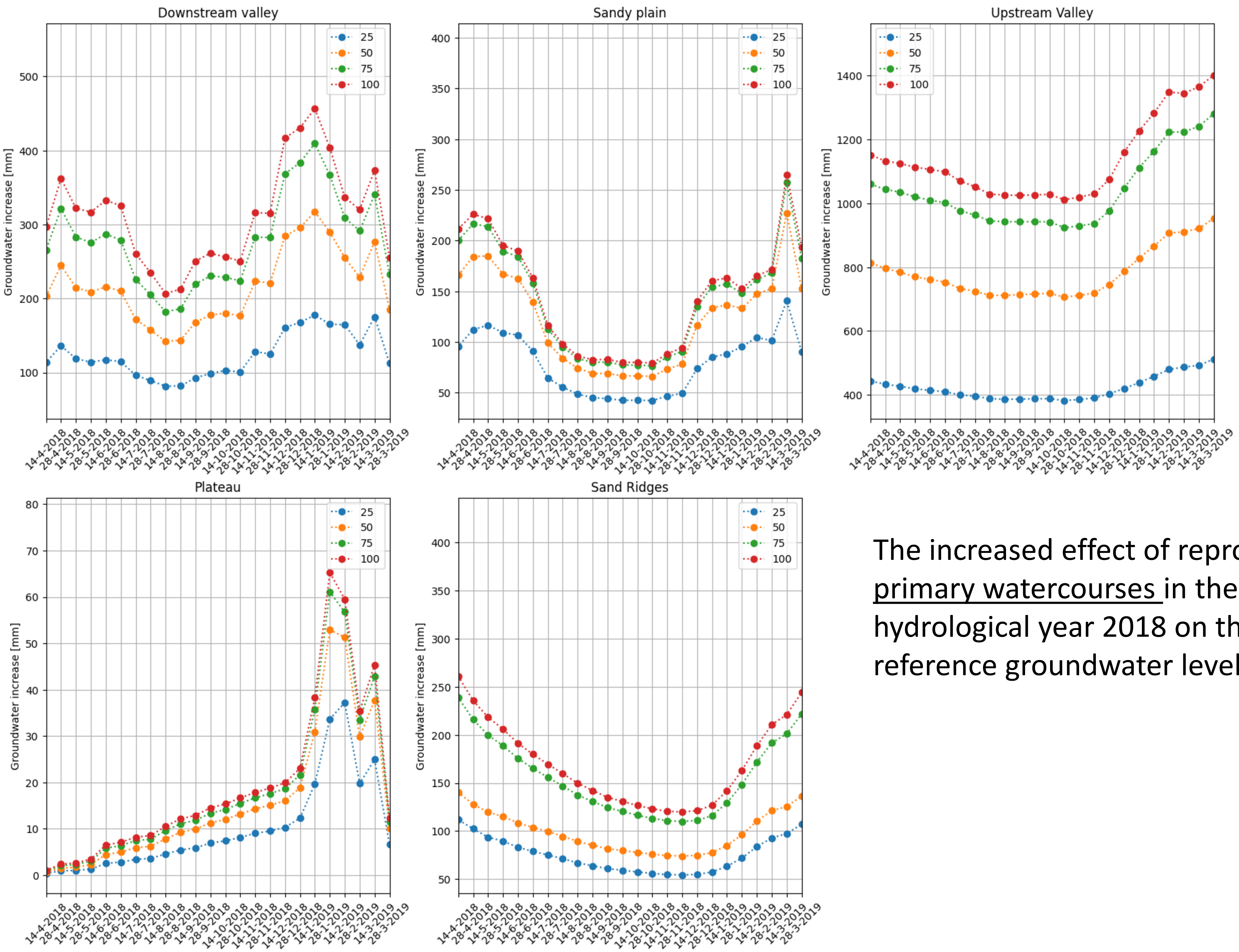


*Reprofiling secondary watercourses - increase in GVG with respect to the reference scenario [m]*

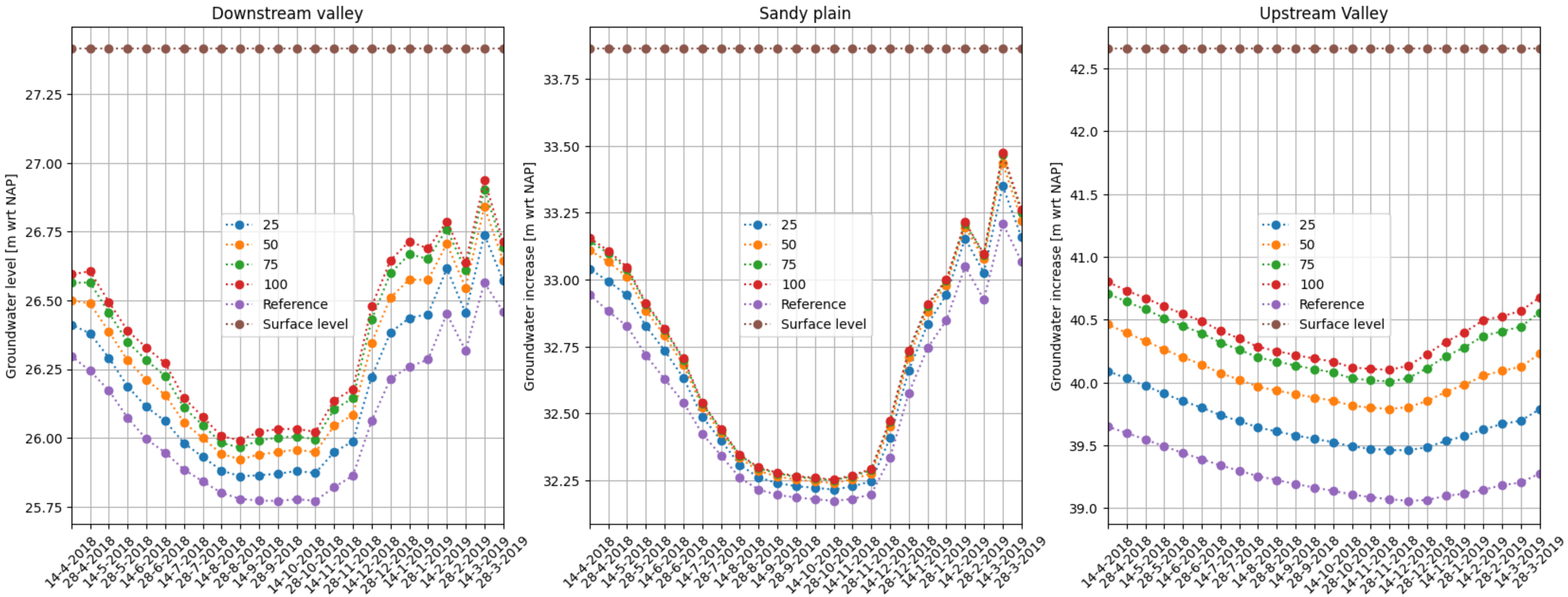


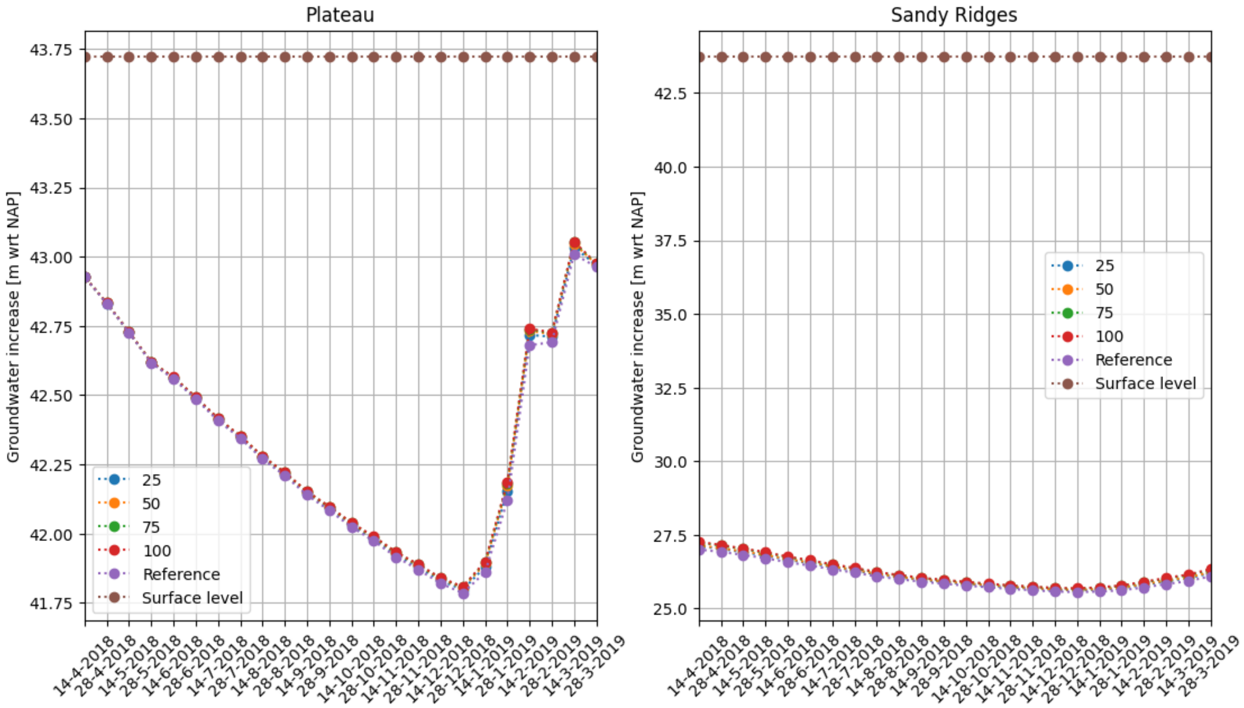
## Appendix C : Time series analysis and boxplots of the reprofiling measures

# Primary watercourses

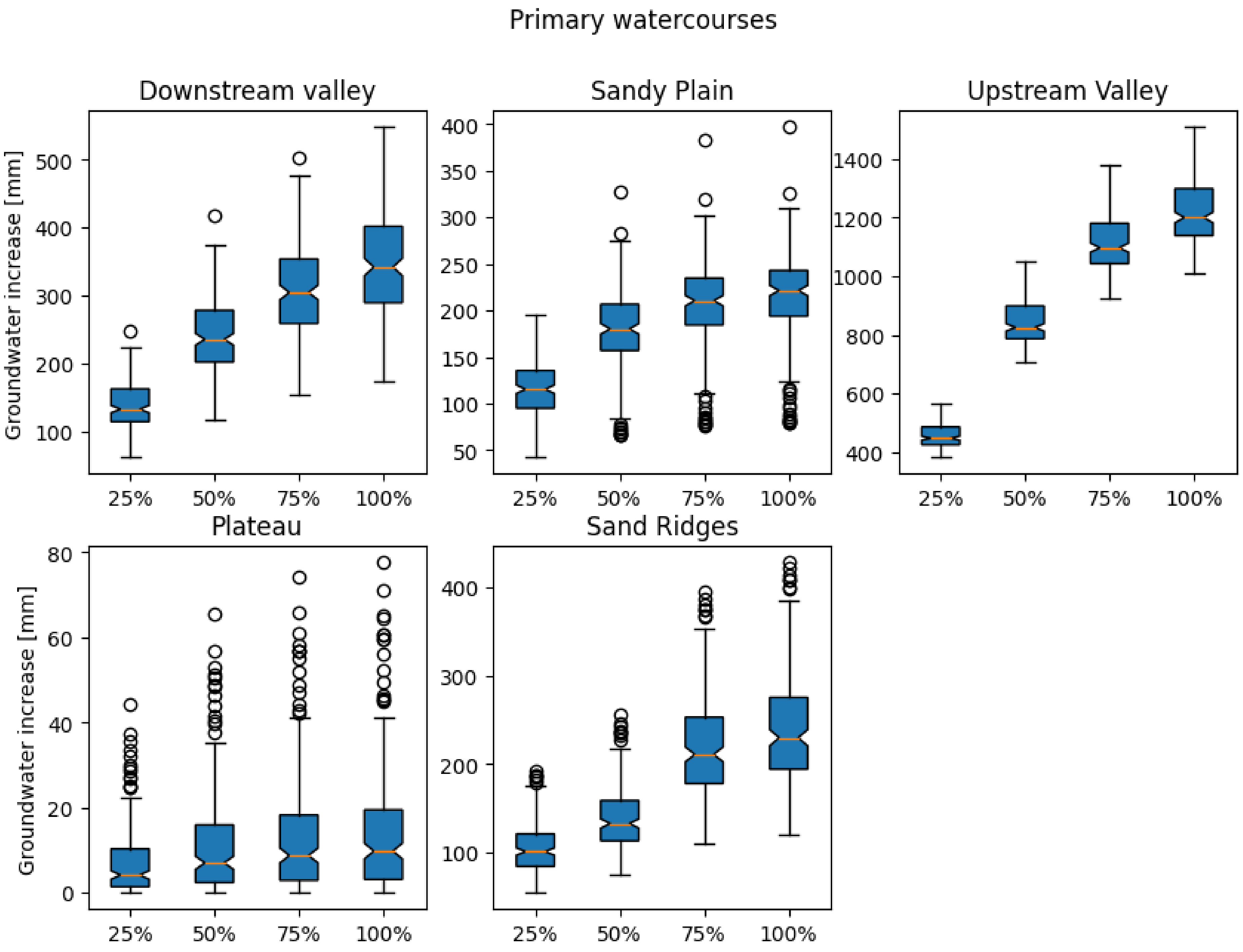



The increased effect of reprofiling <u>primary watercourses</u> in the hydrological year 2018 on the reference groundwater level [m]

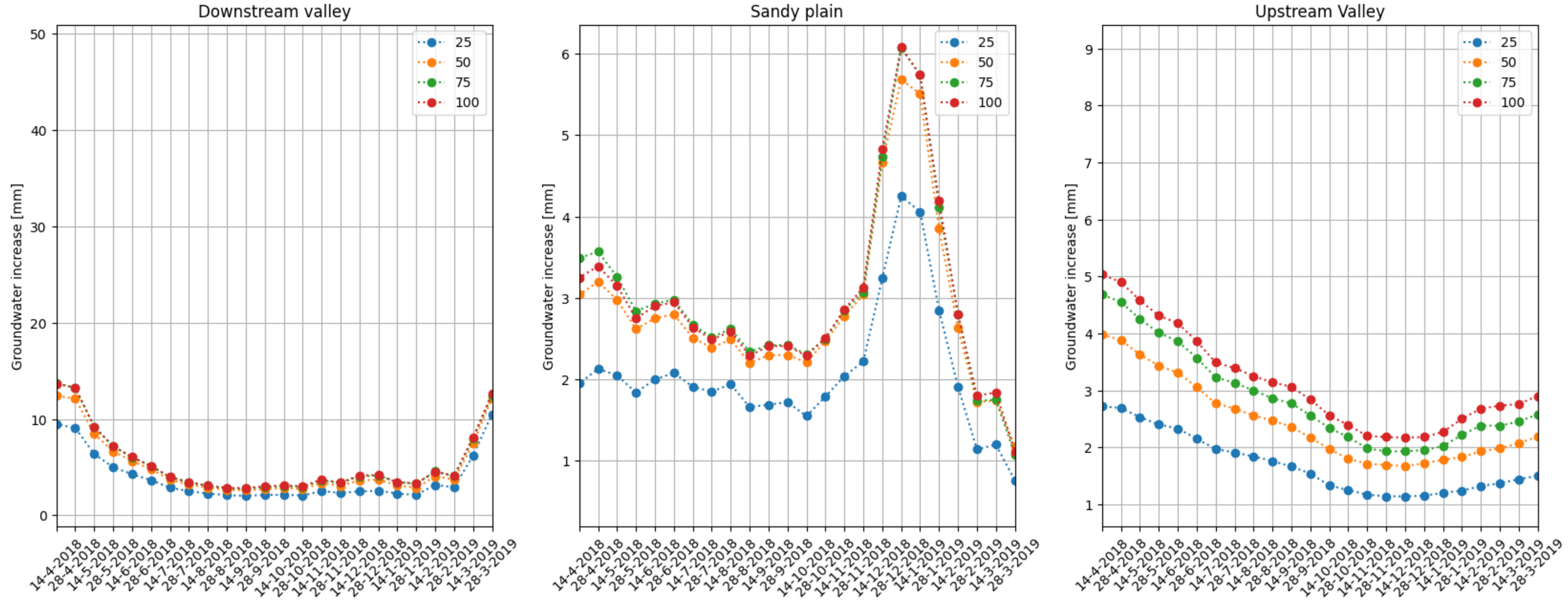


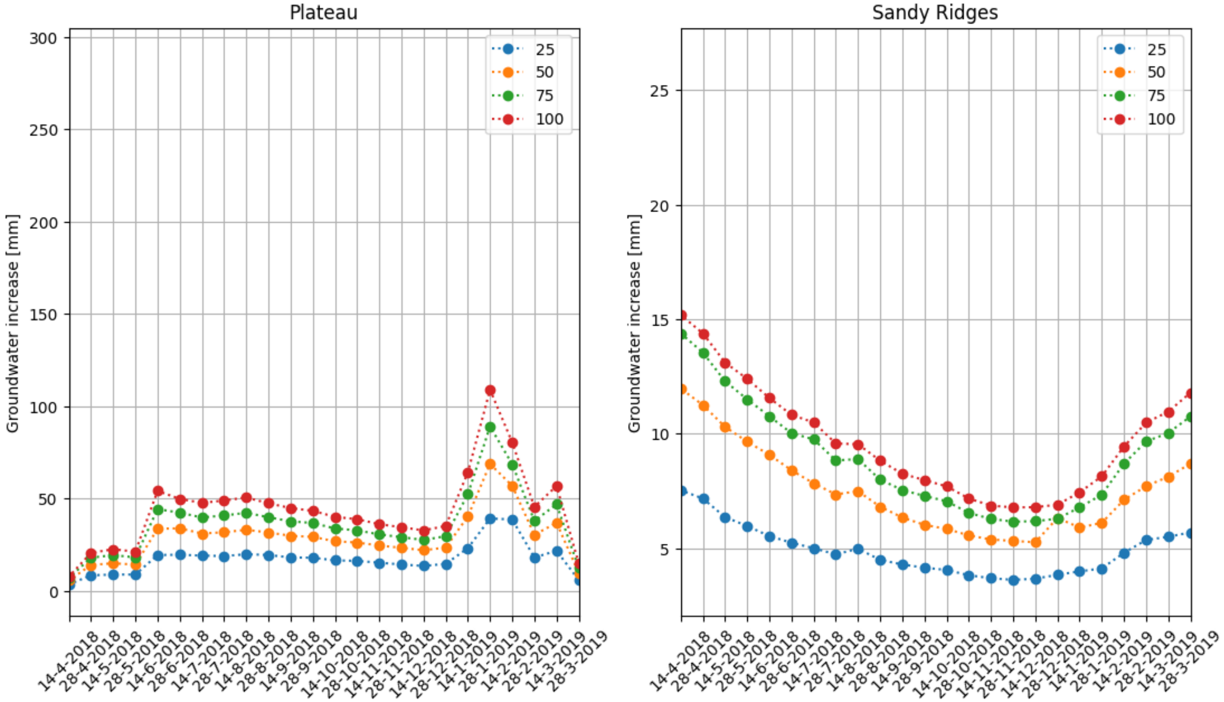




The increased groundwater levels with respect to the surface level by reprofiling primary watercourses in the hydrological year 2018

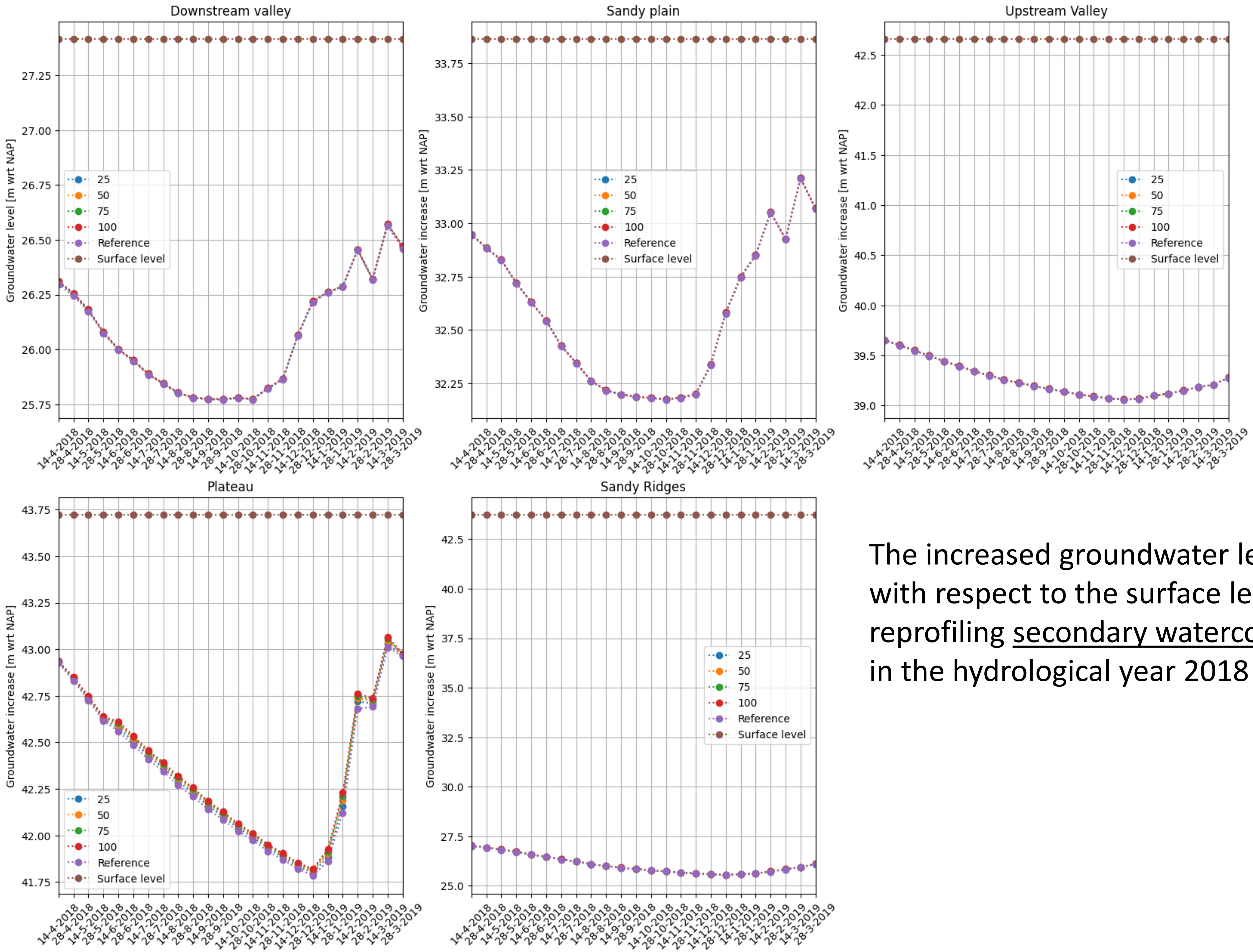

Primary watercourses
Downstream valley
Sandy Plain
Upstream Valley
Plateau
Sand Ridges
Groundwater increase [mm]
Groundwater increase [mm]
25%
50%
75%
100%
100
200
300
400
500
50
150
250
350
400
600
800
1000
1200
1400
0
20
40
60
80

# Secondary watercourses

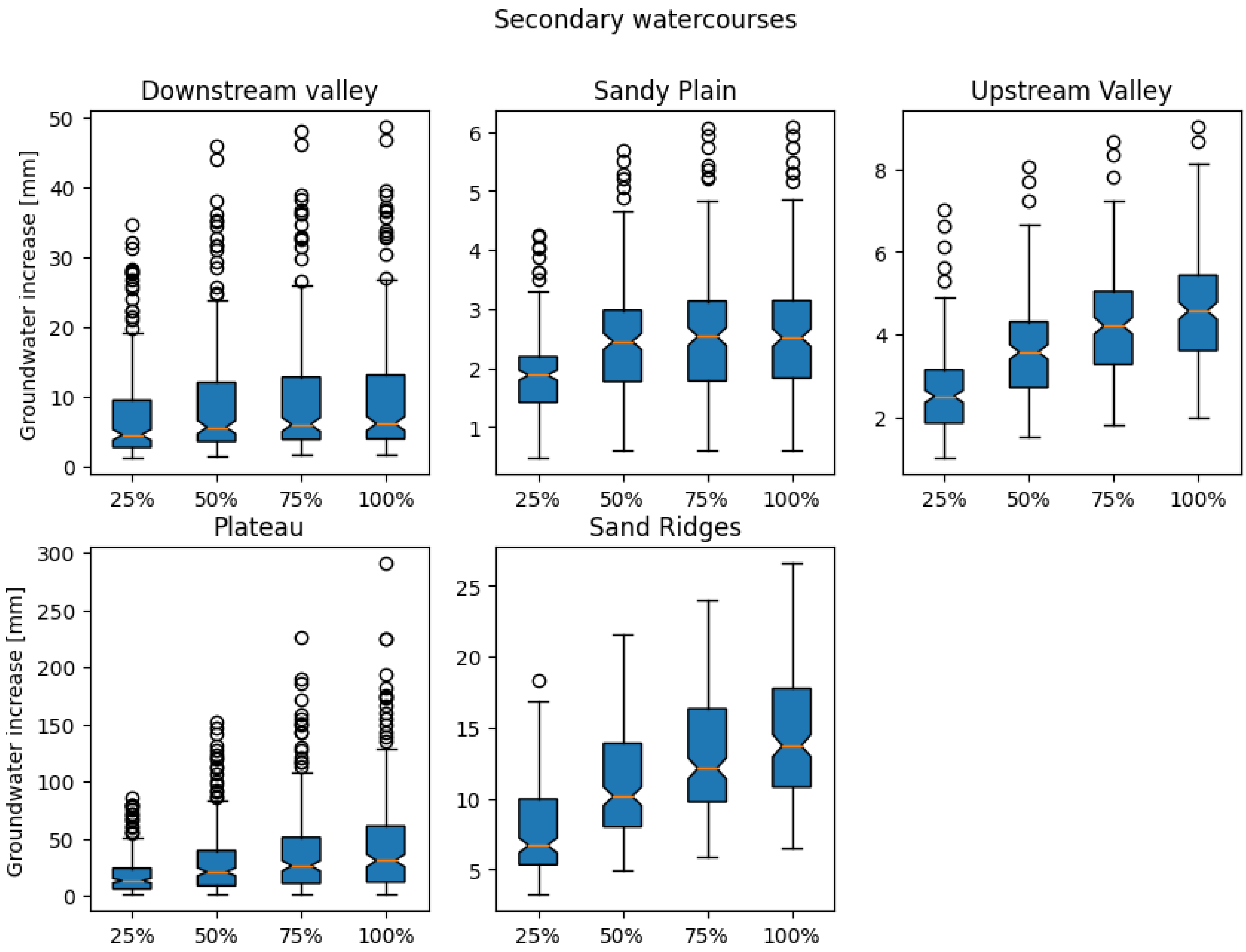



The increased effect of reprofiling secondary watercourses in the hydrological year 2018 on the reference groundwater level [m]

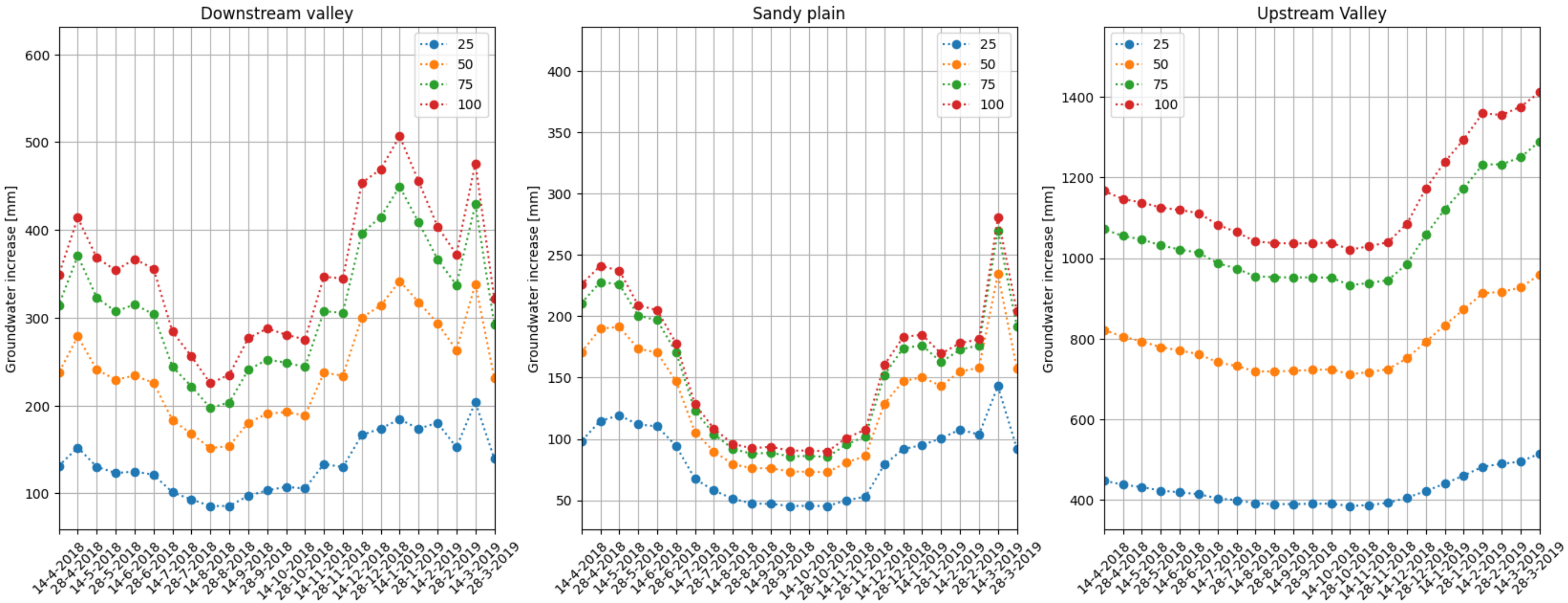


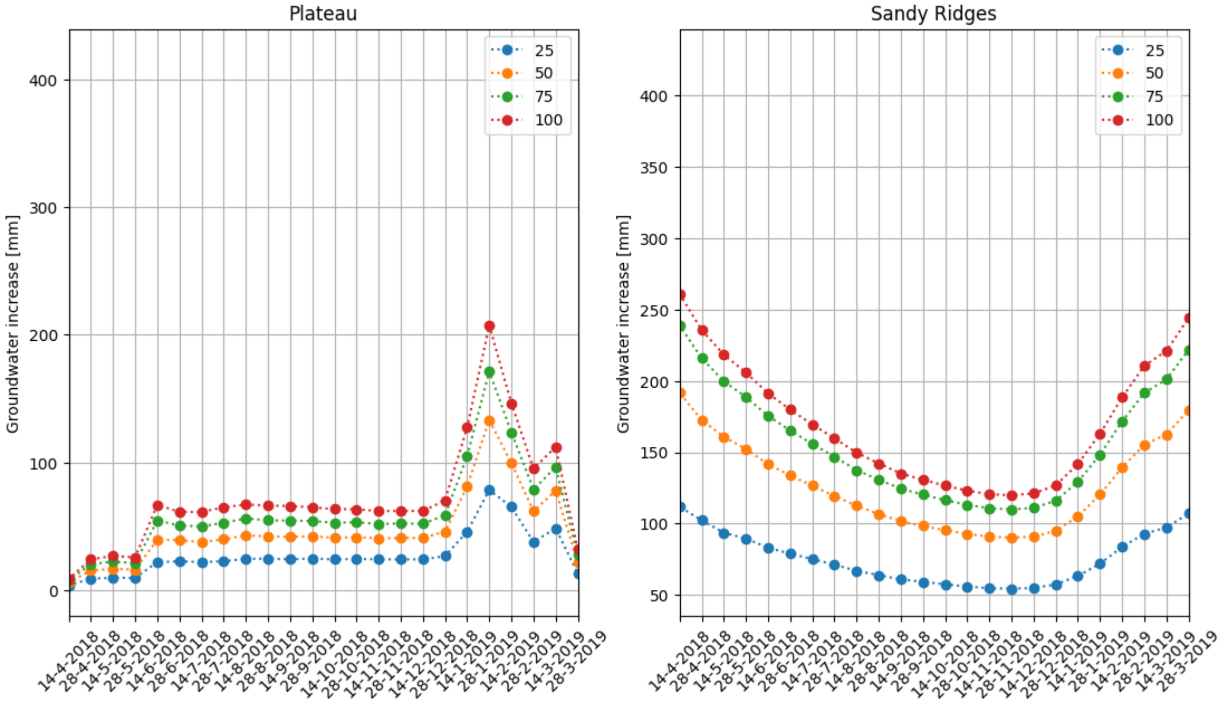

The increased groundwater levels with respect to the surface level by reprofiling <u>secondary watercourses</u> in the hydrological year 2018



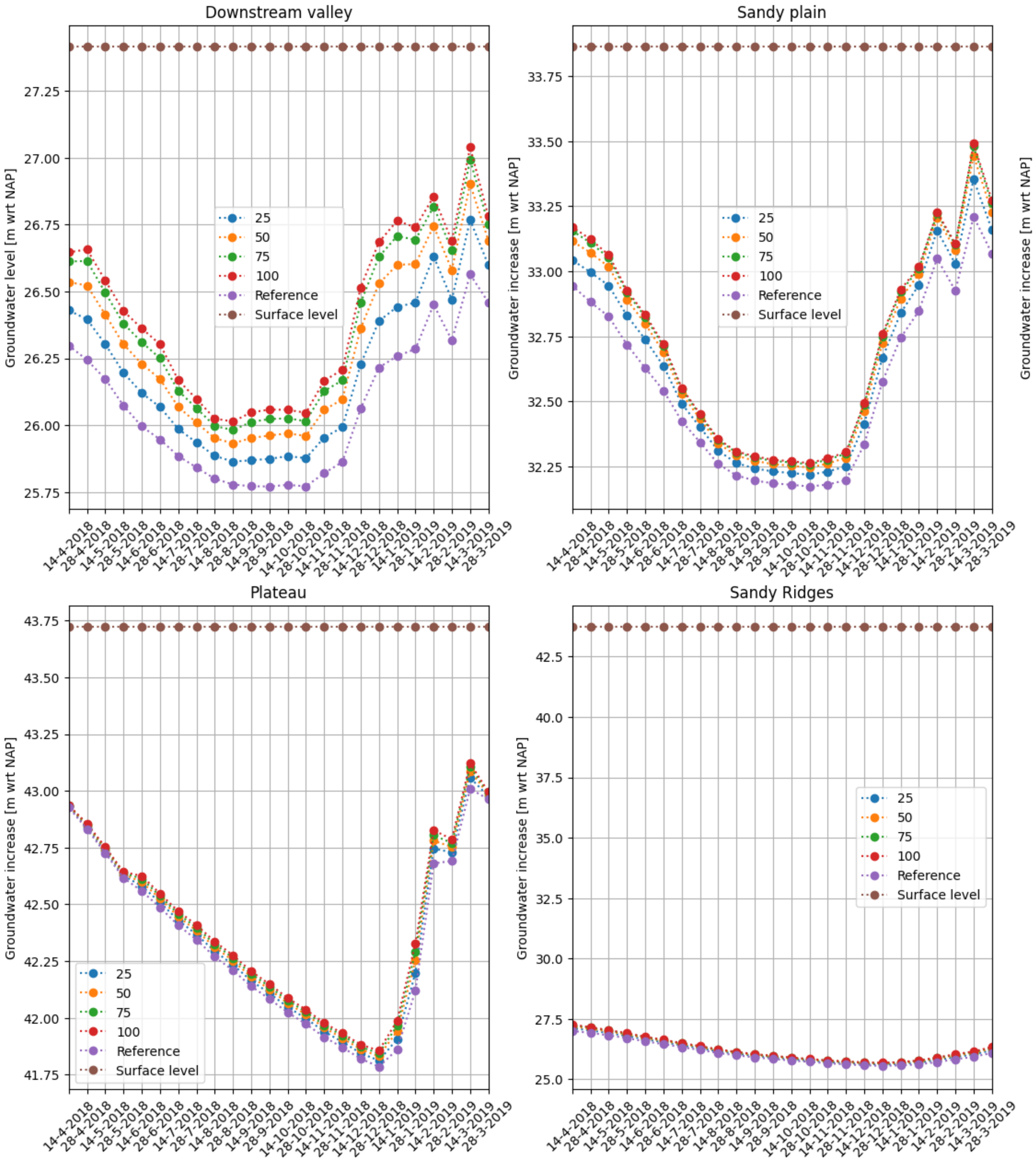
Secondary watercourses
Downstream valley
Sandy Plain
Upstream Valley
Plateau
Sand Ridges
Groundwater increase [mm]
25%
50%
75%
100%

# Primary and secondary watercourses

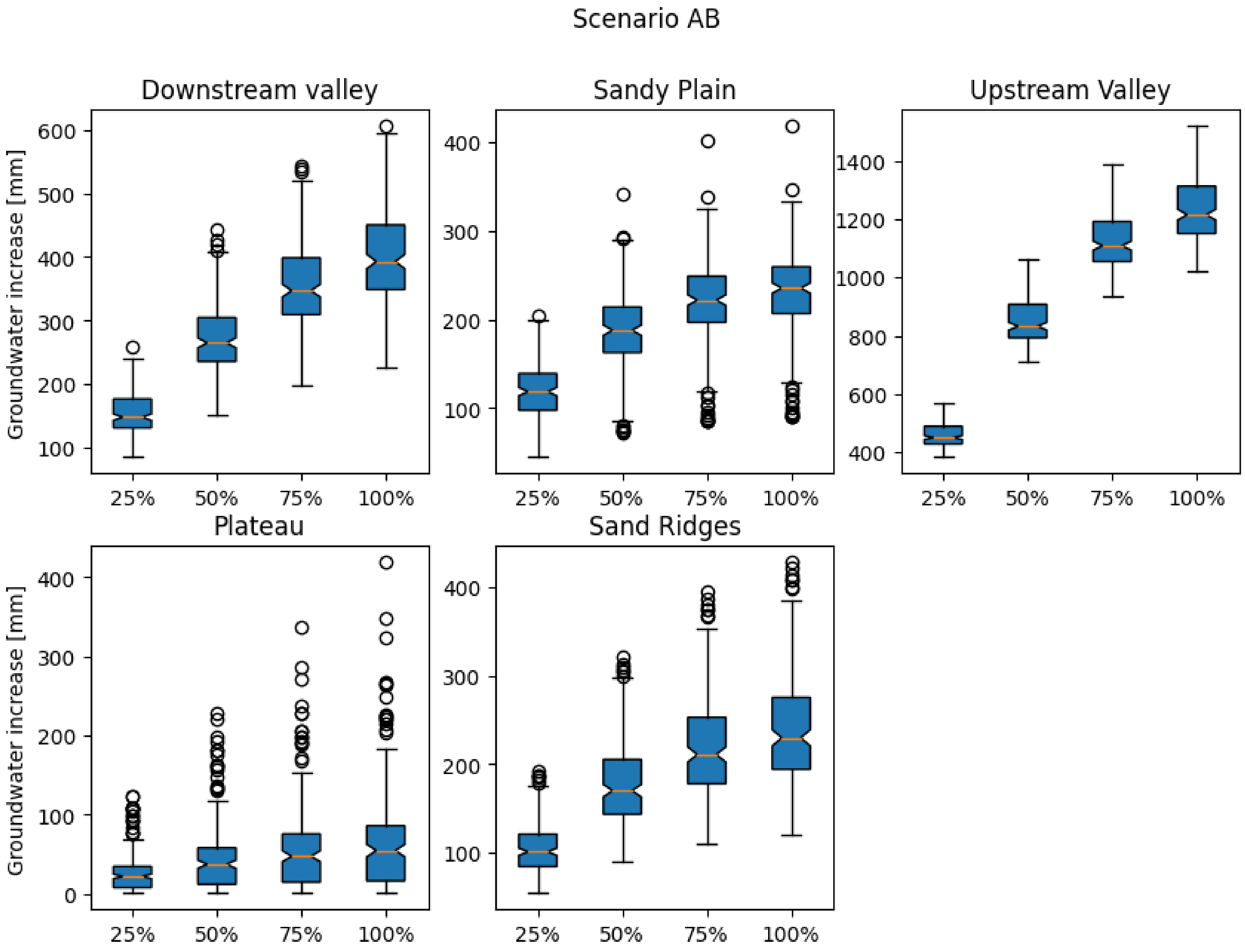



The increased effect of reprofiling primary and secondary watercourses in the hydrological year 2018 on the reference groundwater level [m]

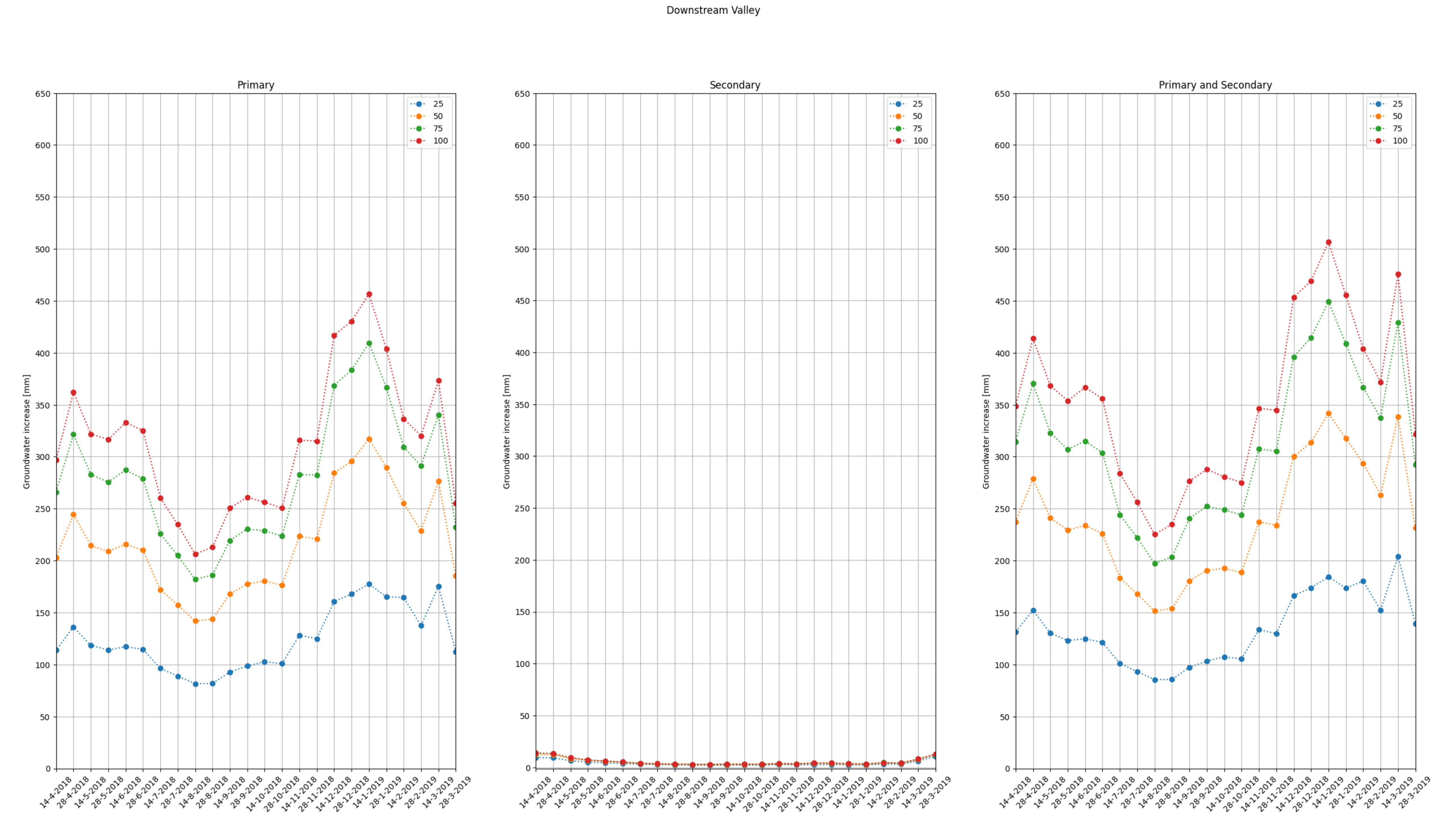


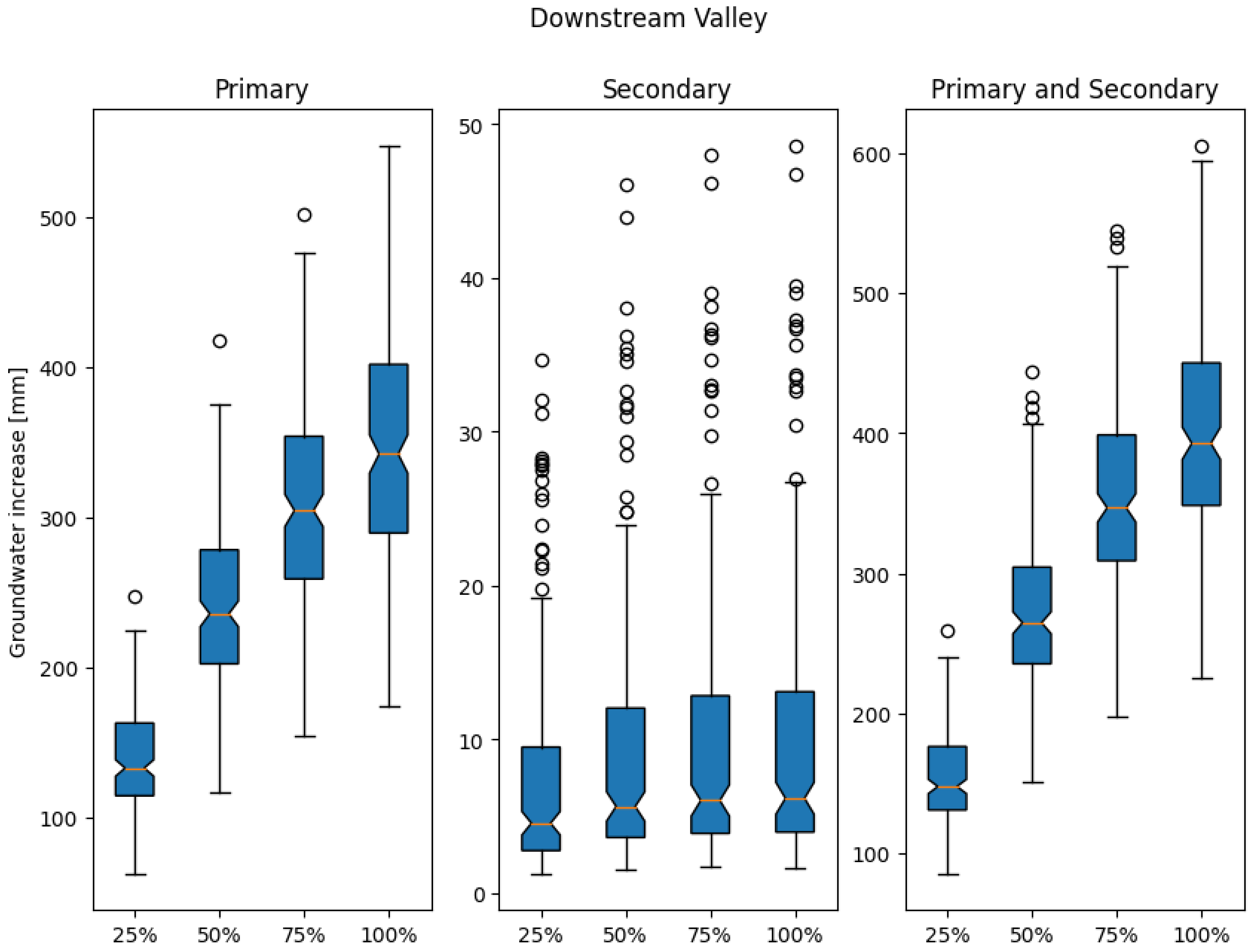

The increased groundwater levels with respect to the surface level by reprofiling primary and secondary watercourses in the hydrological year 2018



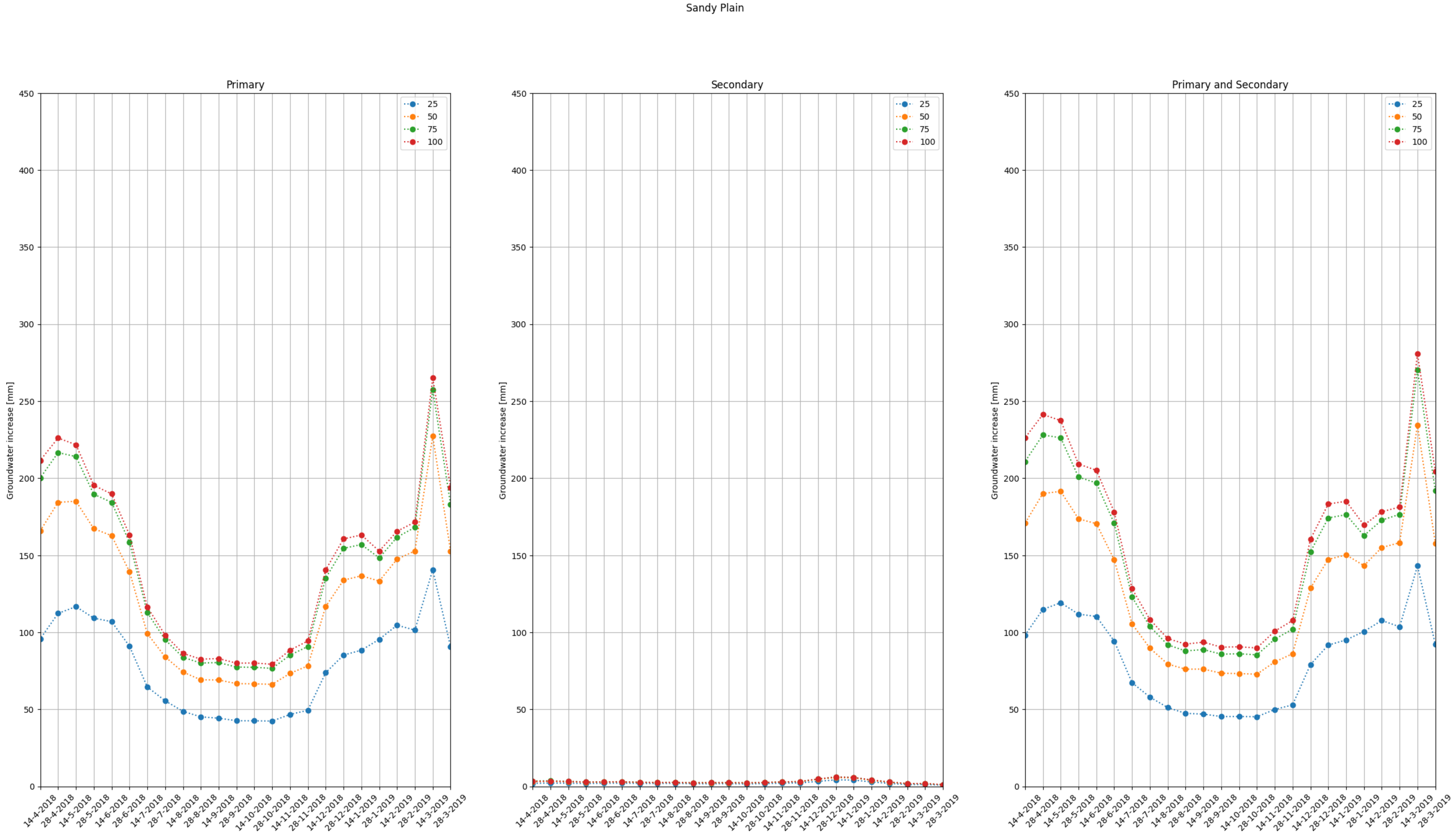
Scenario AB
Downstream valley
Sandy Plain
Upstream Valley
Plateau
Sand Ridges
Groundwater increase [mm]
Groundwater increase [mm]
100
200
300
400
500
600
100
200
300
400
400
600
800
1000
1200
1400
0
100
200
300
400
100
200
300
400
25%
50%
75%
100%

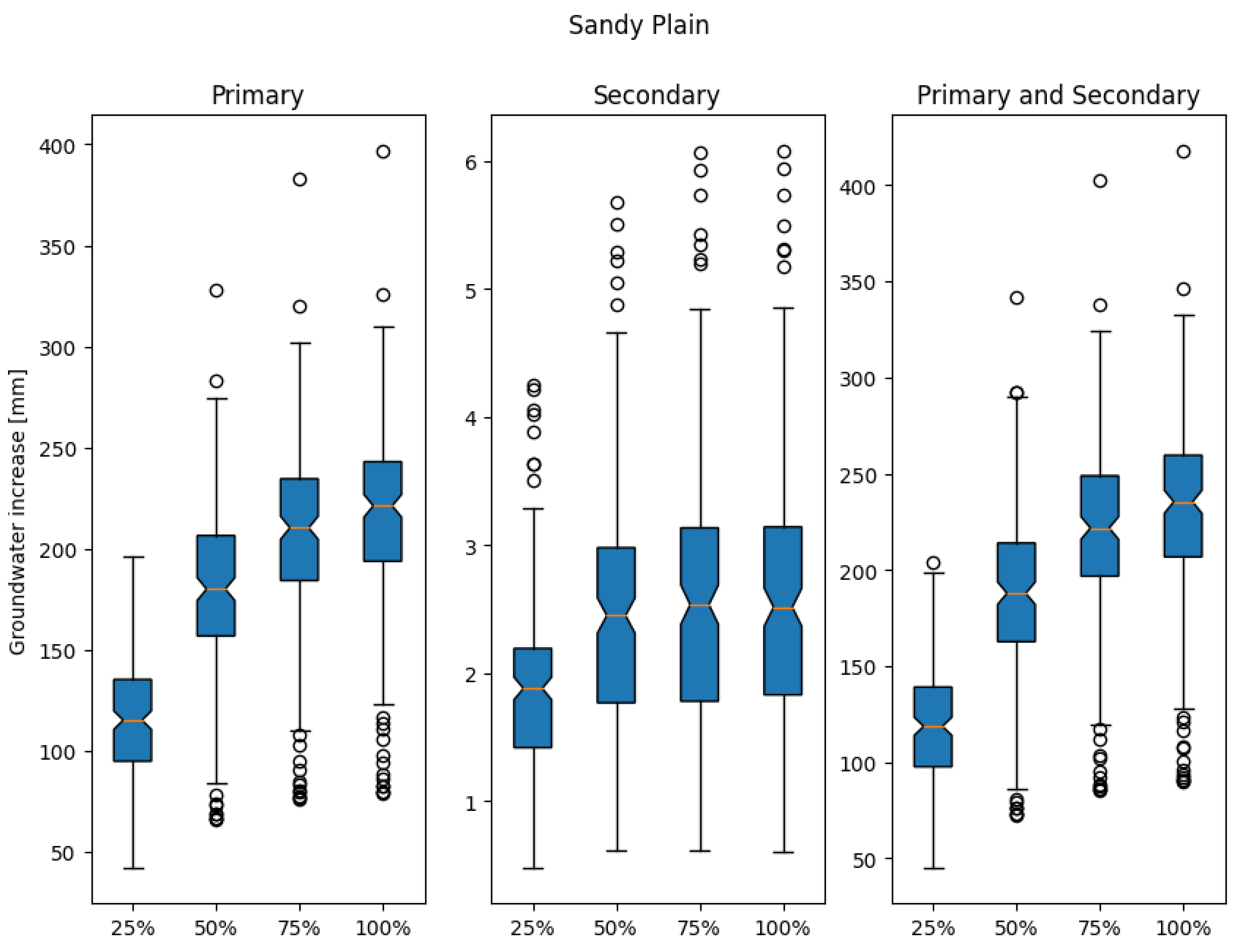
# Compare primary and secondary watercourses

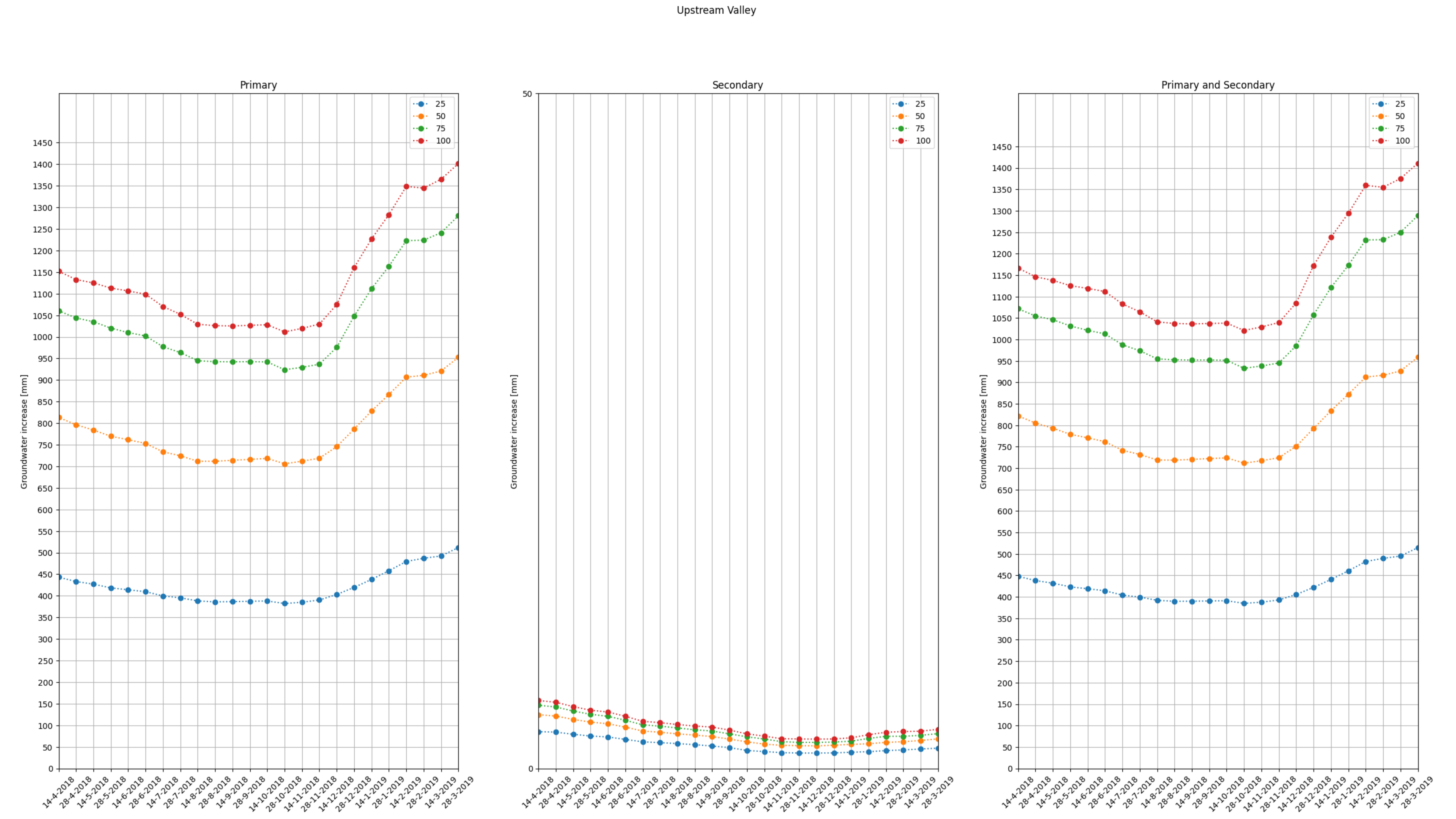

Downstream Valley
Primary
Secondary
Primary and Secondary
Groundwater increase [mm]
25
50
75
100
14-4-2018
28-4-2018
14-5-2018
28-5-2018
14-6-2018
28-6-2018
14-7-2018
28-7-2018
14-8-2018
28-8-2018
14-9-2018
28-9-2018
14-10-2018
28-10-2018
14-11-2018
28-11-2018
14-12-2018
28-12-2018
14-1-2019
28-1-2019
14-2-2019
28-2-2019
14-3-2019
28-3-2019

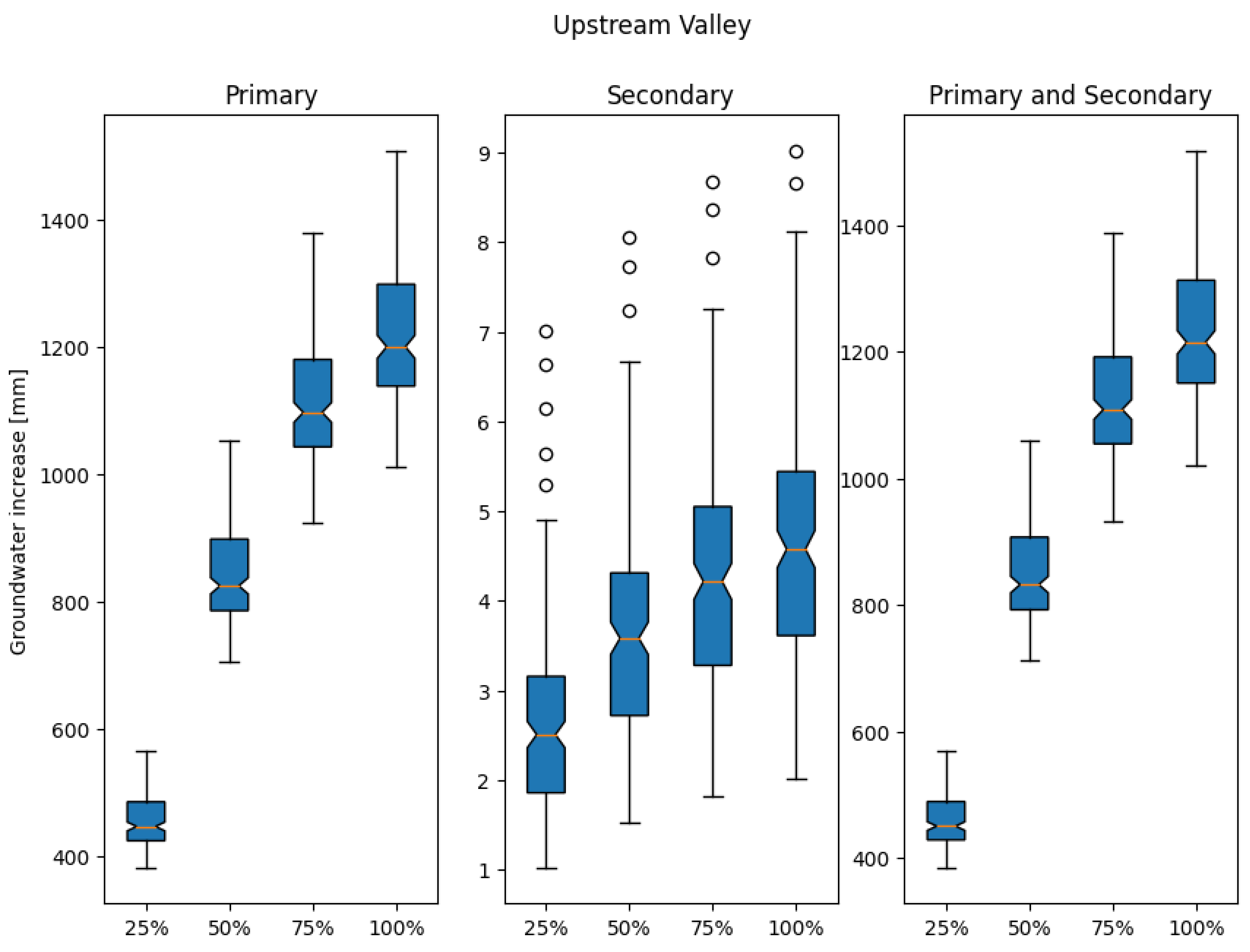


Downstream Valley
Primary
Secondary
Primary and Secondary
Groundwater increase [mm]
100
200
300
400
500
0
10
20
30
40
50
600
25%
50%
75%
100%

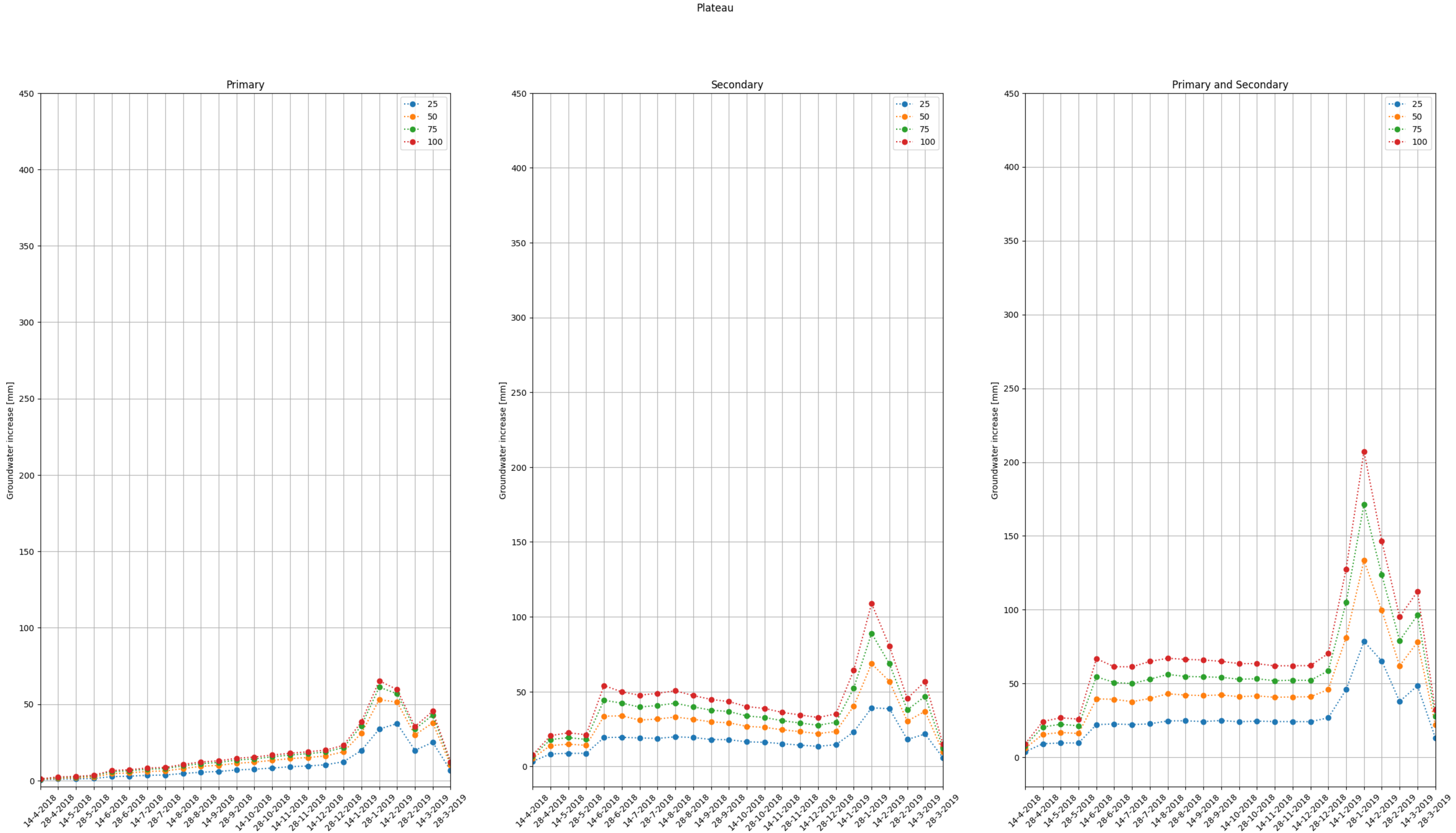

Sandy Plain
Primary
Secondary
Primary and Secondary
Groundwater increase [mm]
25
50
75
100
0
50
100
150
200
250
300
350
400
450
14-4-2018
28-4-2018
14-5-2018
28-5-2018
14-6-2018
28-6-2018
14-7-2018
28-7-2018
14-8-2018
28-8-2018
14-9-2018
28-9-2018
14-10-2018
28-10-2018
14-11-2018
28-11-2018
14-12-2018
28-12-2018
14-1-2019
28-1-2019
14-2-2019
28-2-2019
14-3-2019
28-3-2019

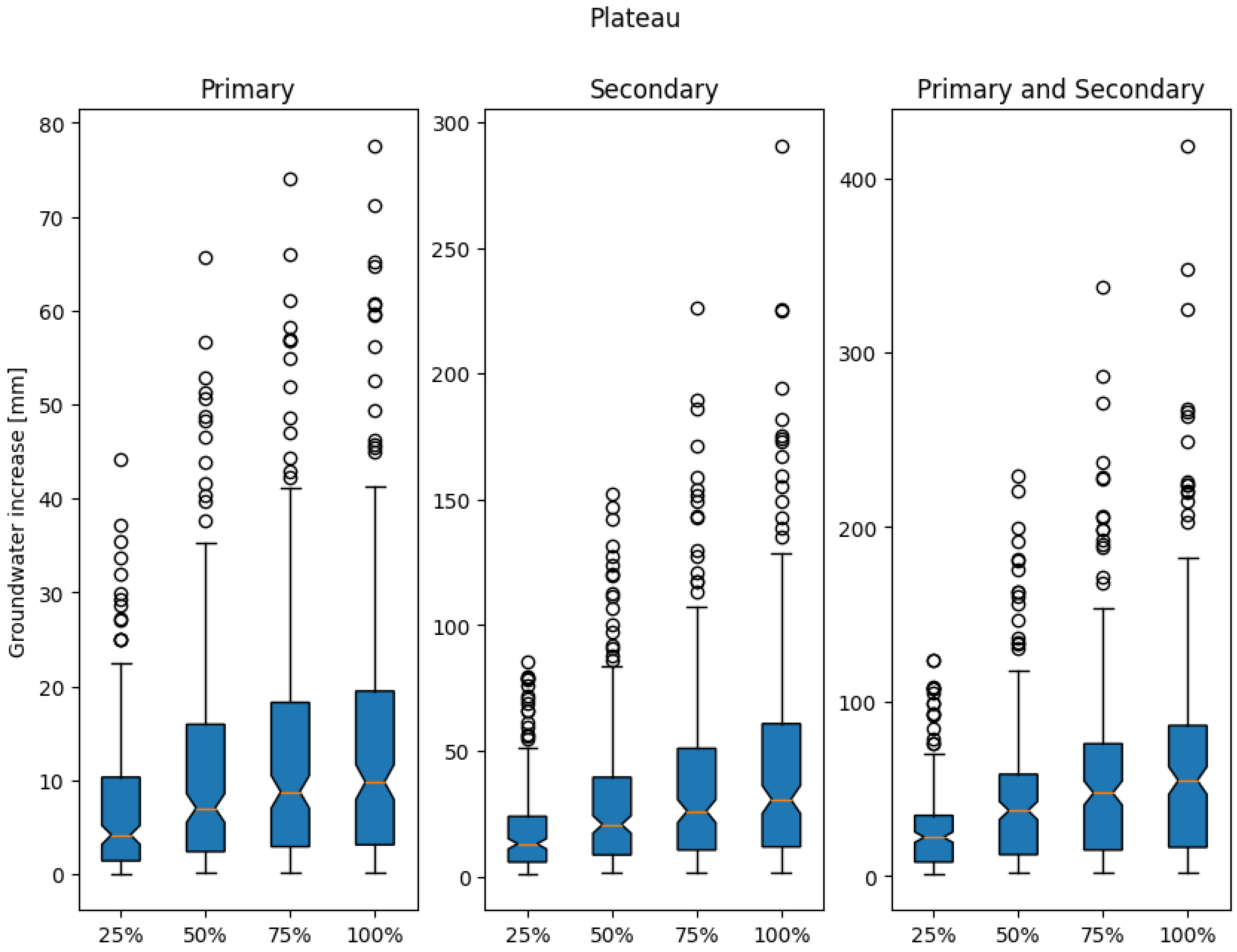

Sandy Plain
Primary
Secondary
Primary and Secondary
Groundwater increase [mm]
400
350
300
250
200
150
100
50
6
5
4
3
2
1
25%
50%
75%
100%


Upstream Valley
Primary
Secondary
Primary and Secondary
Groundwater increase [mm]
25
50
75
100
14-4-2018
28-4-2018
14-5-2018
28-5-2018
14-6-2018
28-6-2018
14-7-2018
28-7-2018
14-8-2018
28-8-2018
14-9-2018
28-9-2018
14-10-2018
28-10-2018
14-11-2018
28-11-2018
14-12-2018
28-12-2018
14-1-2019
28-1-2019
14-2-2019
28-2-2019
14-3-2019
28-3-2019

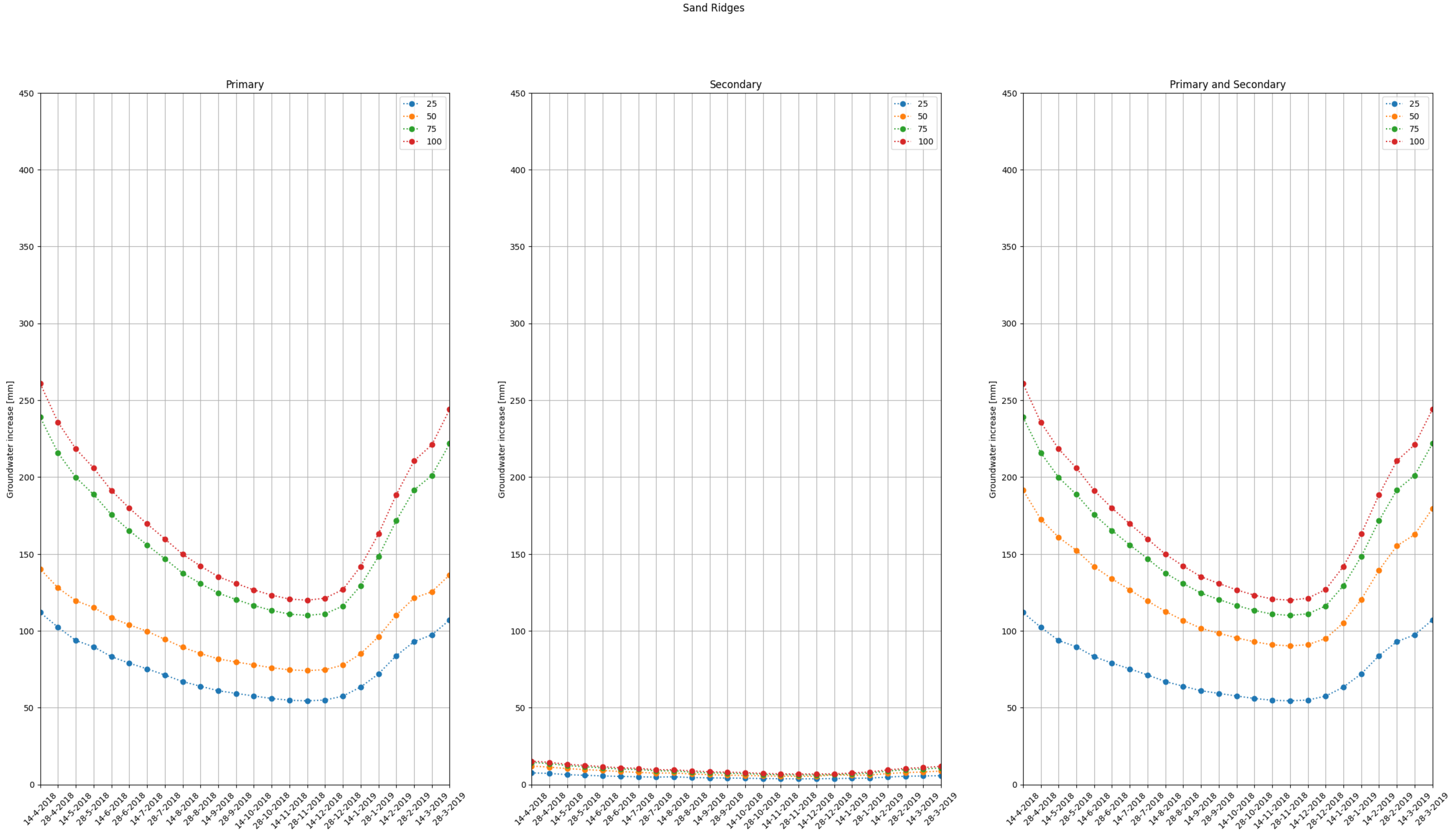


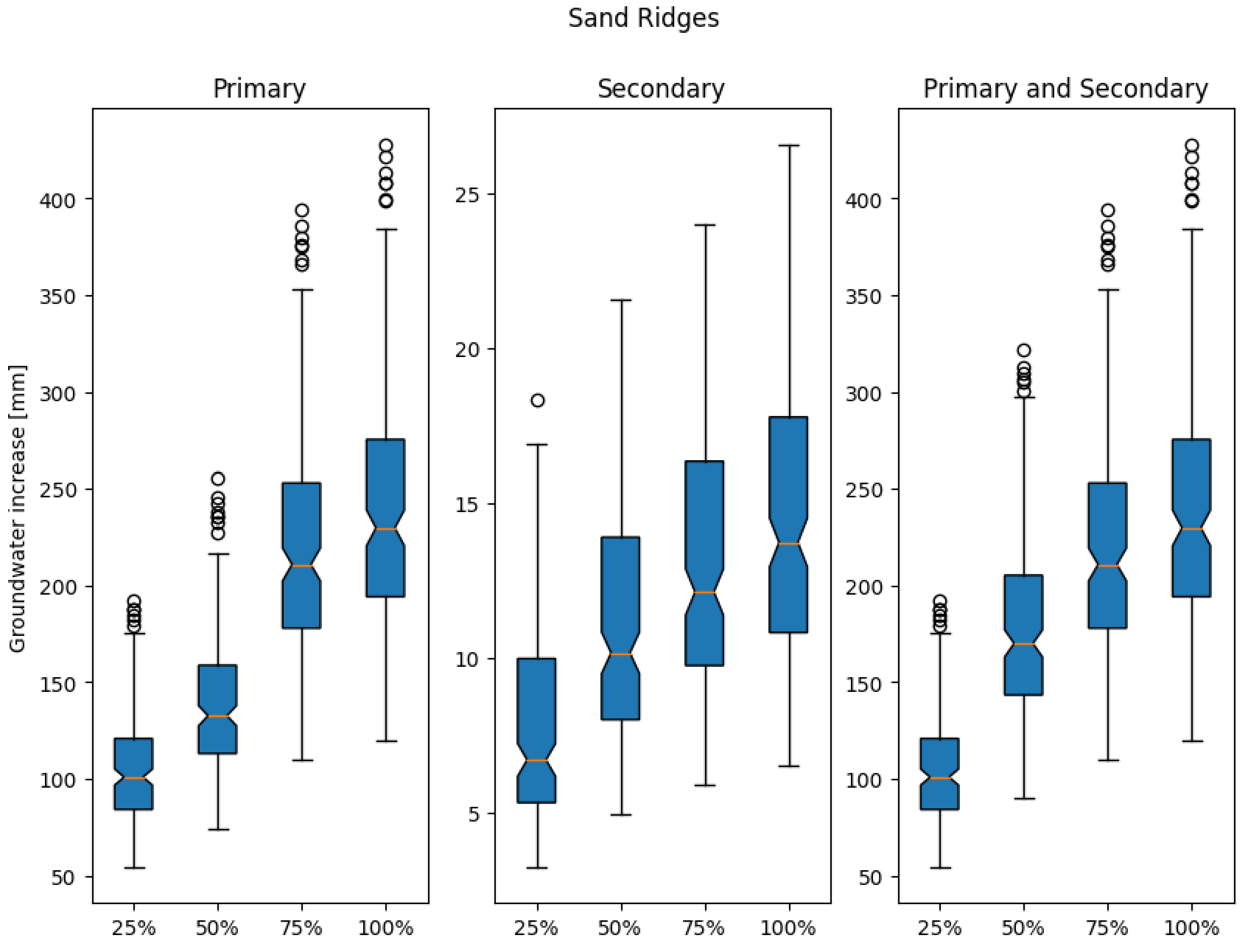
Upstream Valley
Primary
Secondary
Primary and Secondary
Groundwater increase [mm]
400
600
800
1000
1200
1400
1
2
3
4
5
6
7
8
9
25%
50%
75%
100%


Plateau
Primary
Secondary
Primary and Secondary
Groundwater increase [mm]
25
50
75
100
0
50
100
150
200
250
300
350
400
450
14-4-2018
28-4-2018
14-5-2018
28-5-2018
14-6-2018
28-6-2018
14-7-2018
28-7-2018
14-8-2018
28-8-2018
14-9-2018
28-9-2018
14-10-2018
28-10-2018
14-11-2018
28-11-2018
14-12-2018
28-12-2018
14-1-2019
28-1-2019
14-2-2019
28-2-2019
14-3-2019
28-3-2019



Plateau
Primary
Secondary
Primary and Secondary
Groundwater increase [mm]
0
10
20
30
40
50
60
70
80
0
50
100
150
200
250
300
0
100
200
300
400
25%
50%
75%
100%


Sand Ridges
Primary
Secondary
Primary and Secondary
Groundwater increase [mm]
0
50
100
150
200
250
300
350
400
450
25
50
75
100
14-4-2018
28-4-2018
14-5-2018
28-5-2018
14-6-2018
28-6-2018
14-7-2018
28-7-2018
14-8-2018
28-8-2018
14-9-2018
28-9-2018
14-10-2018
28-10-2018
14-11-2018
28-11-2018
14-12-2018
28-12-2018
14-1-2019
28-1-2019
14-2-2019
28-2-2019
14-3-2019
28-3-2019



Sand Ridges
Primary
Secondary
Primary and Secondary
Groundwater increase [mm]
25%
50%
75%
100%