FROM GREY TO GREEN

The effects of replacing garden tiles with grass on the runoff from front gardens and districts

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Abstract

Urban residential gardens are increasingly being paved by people for convenience sake. The near impervious layer that is created in these low maintenance gardens generates problems for the water management of a city. Most sewage systems were implemented without considering residential gardens which means that they are not built for the extra runoff that is caused by this paving trend. Operatie Steenbreek is an organisation that tries to offset these runoff problems. They do this by giving garden owners the opportunity to hand in some of their garden tiles and replace them with soil and plants.

This research analyses the effects of those replacement actions on the runoff from front gardens and districts. Eleven hypothetical front gardens with different percentages of grass surfaces were simulated using a model in the program RainTools. In addition, a case study for the Spoorbuurt district in Nijmegen was conducted. Both the garden and the district scenarios were simulated using multiple precipitation events and a precipitation series.

The results for a 15 m^2 front garden show that for each 1% replacement of garden tiles with grass, the runoff decreases by 2.5% during a precipitation event with a return period of a year. However, the extent of the decrease in runoff differs per precipitation event. When 50% of its surface exists of grass, the garden has no runoff occurring during the precipitation series of the year 2013.

Although the model that was used helped to quantify and visualise the effects of the greening, there should be considered that it was a simplified model. Therefore, only the main features of the runoff systems were studied and the outcomes are thus indicative. Further research with a more detailed model could lead to more realistic results.

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Preface

Since the second year of my BSc Soil, Water, Atmosphere I have been leaning towards the water side of the study. The choice for the topic of this bachelor thesis was therefore fairly easy to make. This subject gave me a chance to delve into a problem which is in my field of interest and at the same time solve a social problem.

While conducting this research I have met many wonderful people that were kind enough to help me. First of all, I would like to thank my supervisor Klaas Metselaar. You gave me enough space to conduct my own research but at the same time made sure I was on the right track. Secondly, I want to thank Harry van Luijtelaar from Stichting RIONED for letting me use the program RainTools and helping me along the way. Without you I would probably still be struggling with the right layer connections. I would also like to thank Joop Spijker from Operatie Steenbreek for helping me come up with ideas and inviting me to the Knowledge and Inspiration day of Operatie Steenbreek. Lastly, I want to thank the Municipality of Nijmegen for providing me their districts dataset.

1. Introduction

Plants out, garden tiles in. This has been one of the major trends in urban residential gardens in the past decade (Perry and Nawaz, 2008). According to the London Assembly Environment Committee (2005), the reason for this transition to grey is that paved gardens require less maintenance and create additional parking space. This growth in garden tiles usage, however, means an increase in impermeable surface area, which has a significant effect on the hydrological cycle of urban areas (Scalenghe and Marsan, 2009). By sealing the ground, the garden tiles prevent rainwater from infiltrating into the soil which causes the volume and velocity of surface runoff to increase (Verbeeck et al., 2011). In addition, the frequency of heavy precipitation events is predicted to increase in the future (Pachauri and Reisinger, 2007). According to Stichting RIONED, residential gardens are often not considered when calculating the capacity of a sewage system. The increase in paved areas in these gardens will therefore load the sewers beyond what they are expected to handle. Consequently, the risk of nuisance floods in urban areas is enhanced due to a higher pressure on the sewage system (Natale and Savi, 2007). Projects such as the Dutch 'Operatie Steenbreek' are trying to raise awareness about the effects of this growing urban trend. They help cities with counteracting the soil sealing by informing the citizens and giving them the opportunity to hand in their garden tiles and get fertile soil and plants in return (Cornelissen, 2018).

Verbeeck et al. (2011) concluded that research is needed on the spatial distribution of paved surfaces and how they influence hydrological systems at garden scale. This is because of the complicated configuration of gardens and their boundaries which are sometimes difficult to determine. An analysis which addresses this topic has quite recently been done by Zwaagstra (2014). She researched soil sealing in urban private gardens and its contribution to runoff. The effects that directly connected paved areas have on the runoff, on the other hand, have to our knowledge not been researched. Analysing different scenarios using a model could therefore lead to a better understanding of the effect that actions undertaken by organizations such as Operatie Steenbreek have on the runoff of urban areas. The generated results can also give insight in the differences in impact on a smaller and a larger scale. These numerical outcomes help visualising and quantifying the effects and can be used to inform people about the importance of greening their gardens.
This study aims to find out how the runoff from a front garden and a district during a precipitation event and series are affected by the replacement of garden tiles with grass, as a result of e.g. Operatie Steenbreek.
This will be done by addressing the following sub questions:

- What types (considering magnitude, duration and return period) of precipitation events cause runoff and are therefore relevant?
- To what extent are urban surface areas altered by replacement actions that are organized by organizations such as Operatie Steenbreek?
- How can the runoff of a garden and a city district be modelled?

Because of the accessibility and higher likelihood of being paved (Perry and Nawaz, 2008), this study focusses only on front gardens instead of the total garden area. Therefore, whenever 'garden' is mentioned in this research it will refer to a front garden.

2. Methods

2.1 Scenarios

For this research eleven hypothetical gardens were simulated using a model that was built with the program RainTools (Stichting RIONED). The gardens had the same total surface area, but each garden had a different paved area fraction. This way they represented different percentages of tile replacement, varying from 0 to 100% grass.

Furthermore, a case study was simulated for the Spoorbuurt district in Nijmegen. In this area Operatie Steenbreek executed tile replacement actions. The initiative resulted in 5200 tiles being replaced. The corresponding data has been used to model the district and a single garden within the district. This data was used so that the real-life actions can be put in perspective by comparing them to the hypothetical garden situations.

2.2 RainTools

This study made use of the program RainTools. RainTools is a program from Stichting RIONED, which is an organisation for urban water management and sewage systems in the Netherlands. With RainTools one can create multi-reservoir models to simulate the functioning of rainwater systems (Broks and Luijtelaar, 2015). It contains multiple calculation tools for different outputs. In this research the 'Perceeltegel' and the 'Wijktegel' tools were used. Both these tools can be used to construct a detailed model of the water management of a plot of land. In the Wijktegel it is possible to draw your own surfaces, making it very suitable for the desired district scale. To prevent biased results, the Wijktegel tool was also used to model the garden scenarios. In addition, the Perceeltegel was used to simulate the garden scenarios. The garden results that were produced using this tool are added to the Appendix (A1 and A2). Within the Wijktegel tool one can create different surface layers which have the option to be connected and exchange water flows. In this tool the precipitation events from Leidraad Rioleering are available as input (See Appendix A3). Furthermore, the Wijktegel contains multiple precipitation series and the possibility to make and analyse a custom precipitation event.

The outputs of the created model are the different water balance terms among which the precipitation (dark blue arrow) is distributed (Figure 1). These terms include amongst others: runoff (orange arrow), infiltration (light green/grey arrow), storage on the surface (light blue rectangle), evaporation (whitish arrow) and storage in the soil (dark green rectangle).

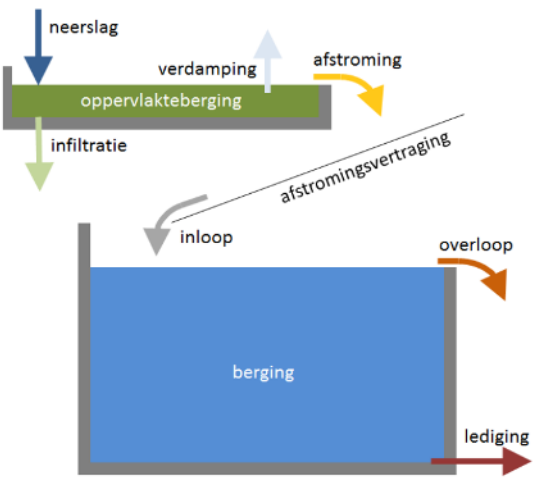


Figure 1 Schematic overview of the water balance used in the Wijktegel tool. Adapted from RainTools (Stichting RIONED).

2.3 Input variables

The model included two different types of surface layers (Figure 2). A paved layer (garden tiles) and an unpaved layer (grass). Both these top layers had the same sublayer.
To simulate the gardens and district, numerous input variables were required for the different characteristics of the various surface layers. The used values together with a description of these variables can be found in the Appendix A4 & A5.

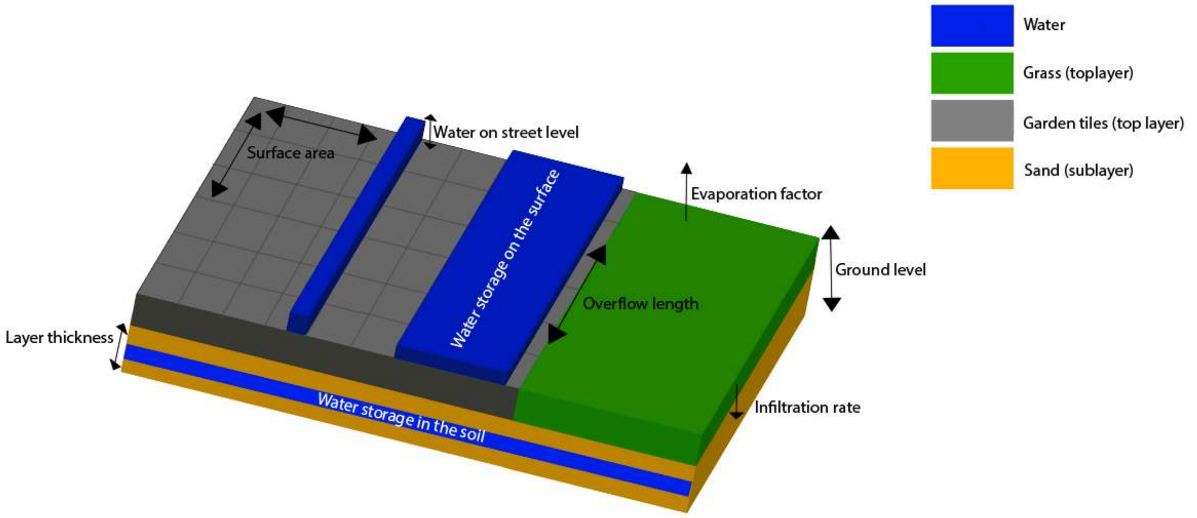


Figure 2 *Overview of the different layers with some their input variables which were implemented in the Wijktegel.*

2.3.1 Reasoning behind the used top layer values

The ground level: a plane horizontal surface is assumed.
The water on street level: assumed, based on average sidewalk heights that were observed in the field.
Water storage in the soil: assumed, based on examples from Stichting RIONED.
Water storage on the surface: assumed, based on examples from Stichting RIONED.
Evaporation factor: similar values assumed for both surface types because of the short-term simulation (events).
Surface area:

- single gardens: based on field research (See Appendix A6).
- district: based on data from case study (See Appendix A7).

Infiltration rate:

- the paved areas are based on Bebelaar and Bakker (1981).
- the grass areas are assumed based on values used in Luijtelaar (2015).

Overflow length:

- single gardens: deducted from the surface area dimensions.
- district: deduced from the surface area dimensions of the Spoorbuurt district.

2.3.2 Reasoning behind the used sublayer values

Layer thickness: assumed, based on standard sandy subsoil values (de Groene campus, 2015)
Porosity: based on values of a sandy subsoil (Geys, 1988)
Permeability: based on values of a sandy subsoil (Geys, 1988)

2.3.3 Precipitation

For both the district and the garden situations the precipitation events R05 and E03 from the Leidraad Riolering were used for the simulations. During R05, 16.8 mm fell in 75 min with the peak in the beginning of the event. It has a return period of a year (T= 1 year). E03 is a more extreme event in which 47.2 mm fell in 180 min with a peak in the middle of the event. This event has a return period of 5 years (T= 5 years).

Research was conducted with R05 because it is of sufficient magnitude to cause runoff in most studied cases. E03 was chosen because of its longer duration and the potentially high runoff. Besides these precipitation events, the precipitation series of 2013 was also studied. This series was taken from a dataset measured hourly in De Bilt between 1906 and 2014. It was used as a sensitivity analysis to study what the difference in runoff results would be between this series of larger and smaller events over a longer period compared to the single events.

Moreover, a custom precipitation event of 9 mm over 4 hours was created. This precipitation event has been included in the research to see what the effect might be of a drizzle type of rain (low intensity, long duration). It represents a typical Dutch precipitation event and is based on Smits et al. (2004). Evaporation was assumed to be 2 mm/d, based on yearly averages from the KNMI (2017).

2.4 Model

2.4.1 Hypothetical gardens (0-100% replaced)

For the modelling of the hypothetical gardens, the total area of each garden was assumed to be 15 m^2. The first situation represented a garden of which the surface contained only garden tiles (Figure 3, top left plot). This plot represented the lowest possible greening (0%). The next garden was similar to the first situation but now a section of 1.5 m^2 in the southern part of the garden was replaced by grass (10% greening). The paved and grass layers were then grouped so that the model would identify it as one plot for output graphs. The water that flowed over the paved layer discharged to the grass layer. This way all the simulated precipitation that fell on the paved layer would flow to the grass layer, which in its turn discharged out of the system. By doing this the runoff of the total plot could be determined from the term 'overspill'.

This process was repeated for nine more garden simulations, each time decreasing the surface area of the paved layer and respectively increasing the surface area of the grass layer by 1.5 m^2. Consequently, the eleventh garden consisted of only the grass layer. This last simulation therefore represented the highest possible replacement (100%) (Figure 3, bottom right corner).

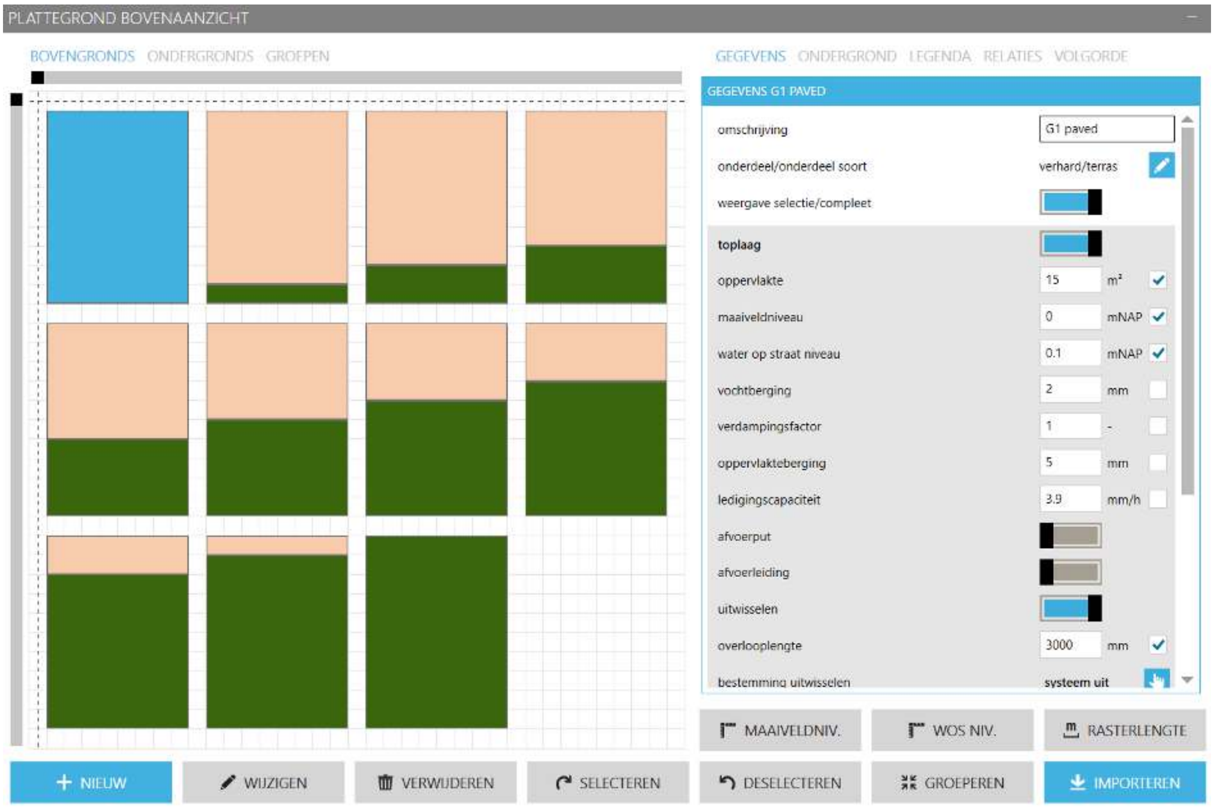


Figure 3 *Top view window of the hypothetical gardens in the Wijktegel tool from RainTools, showing the spatial configuration of the different surface layers and the input variables for the selected layer 'G1 paved' (blue colored because it's selected).*

2.4.2 Spoorbuurt Gardens

Two garden plots were simulated which represented actual gardens from the Spoorbuurt district. Each plot had a total surface area of 15 m².

The first simulation (Appendix A8, left plot) represented the garden before the replacement actions had taken place. The grey to green ratio in this situation was based on data from the municipality of Nijmegen. For the area of the two surface types this meant a 10.185 m² paved layer (67.9%) and a 4.815 m² grass layer (32.1%).

The second simulation (Appendix A8, right plot) represented the garden after the replacement actions. On average 7.5 tiles per garden were replaced during the initiative. This resulted in an increase of the grass layer and respectively a decrease of the paved layer by 0.675 m² (7.5 x 0.09 m^2). The surface area of the paved and the grass layer was thus 9.510 m² (63.4%) and 5.490 m² (36.6%) respectively.

2.4.3 Spoorbuurt District

Two plots were simulated which now represented a simplification of the Spoorbuurt district (in which no distinctions were made between public and private areas). This meant that each plot had a total surface area of 44.713 m².

The first simulation (Appendix A9, left plot) represented the district before the replacement actions had taken place. The grey to green ratio in this situation was based on data from the municipality of Nijmegen. For the area of the two surface types this meant a 27,677 m² paved layer (61.9%) and a 17,036 m² grass layer (38.1%).

The second simulation (Appendix A9, right plot) represented the district after the replacement actions. In total (combining private and public areas) 5200 garden tiles were replaced during the initiative. This resulted in an increase of the grass layer and respectively a decrease of the paved layer by 468 m² (5,200 x 0.09 m^2). The surface area of the paved and grass layer was thus 27,209 m² (60.9%) and 17,504 m² (39.1%) respectively. This means that the initiative of Operatie Steenbreek lead to a replacement of 1% of the total area.

3. Results

The output of the model is a water balance table with a corresponding graph for each layer group (read 'piece of land') that is defined in the model. The table lists the volume of each term of the water balance as a result of the simulated precipitation event or series. The graph depicts these different terms in respect to time. On the right the relevant terms and their colour are listed. The orange term 'overspill' is defined by the exchange destination of the grass layers. Because in each scenario this is set to 'out of the system', this term is similar to the runoff. In this study the orange colour represents the runoff.

Overspill (=Runoff)
Infiltration
Storage on the surface
Evaporation
Storage in the soil

3.1 Hypothetical gardens (0-100% replaced)

3.1.1 Precipitation events

Table 1 and 2 show the amount of runoff during R05 and E03 for the eleven different gardens respectively. Also included is the runoff reduction in comparison to a completely paved garden (0% grass area).

During R05 (T=1 year) the runoff of a completely paved garden is reduced by about 50% when 20% of the area is replaced by grass. From 50% grass area or more, there is no runoff occurring (Table 1).
In case of E03 (T=5 years) a 50% reduction is reached at a 40% grass area. Zero runoff is not achieved in any of the gardens during this precipitation event (Table 2).

Table 1 *Amount and reduction of runoff on the hypothetical gardens (consisting of 0-100% grass) during the standard precipitation event R05 (T= 1 year, 16.8 mm in 75 min).*

Grass area (%)	0	10	20	30	40	50	60	70	80	90	100
Runoff (mm)	5.9	4.3	2.9	1.6	0.54	0.0	0.0	0.0	0.0	0.0	0.0
Runoff reduction (%)	-	27.6	51.2	72.2	90.7	100	100	100	100	100	100

Table 2 *Amount and reduction of runoff on the hypothetical gardens (consisting of 0-100% grass) during the extreme precipitation event E03 (T= 5 years, 47.2 mm in 180 min).*

Grass area (%)	0	10	20	30	40	50	60	70	80	90	100
Runoff (mm)	29.0	24.4	20.3	17.1	14.3	11.5	8.8	6.3	4.1	2.6	1.2
Runoff reduction (%)	-	16.0	30.0	40.8	50.6	60.3	69.6	77.9	85.6	91.0	96.0

Figure 4 and 5 show the different terms of the water balance tables as a function of time for each garden type during precipitation events R05 and E03 respectively.

During R05 the total runoff is highest for the *0% grass* group and lowest for the *100% grass* group. The groups *50% grass* up to *100% grass* do not have any runoff. Moreover, the *100% grass* group has the highest infiltration and water storage in the soil but also the lowest water storage on the surface. The *0% grass group* has the lowest infiltration and water storage in the soil but the highest water storage on the surface (Figure 4).
During E03 the total runoff is highest for the *0% grass* group and lowest for the *100% grass* group. The *100% grass* group has the highest infiltration and water storage in the soil but also the lowest water storage on the surface. The *0% grass group* has the lowest infiltration and water storage in the soil but the highest water storage on the surface (Figure 5).

The custom precipitation event (which represented drizzle) did not lead to any runoff in the simulated gardens. Its results and those for the precipitation events R01, R03, R07, R09 and R10 are listed in Appendix A10 - A15.

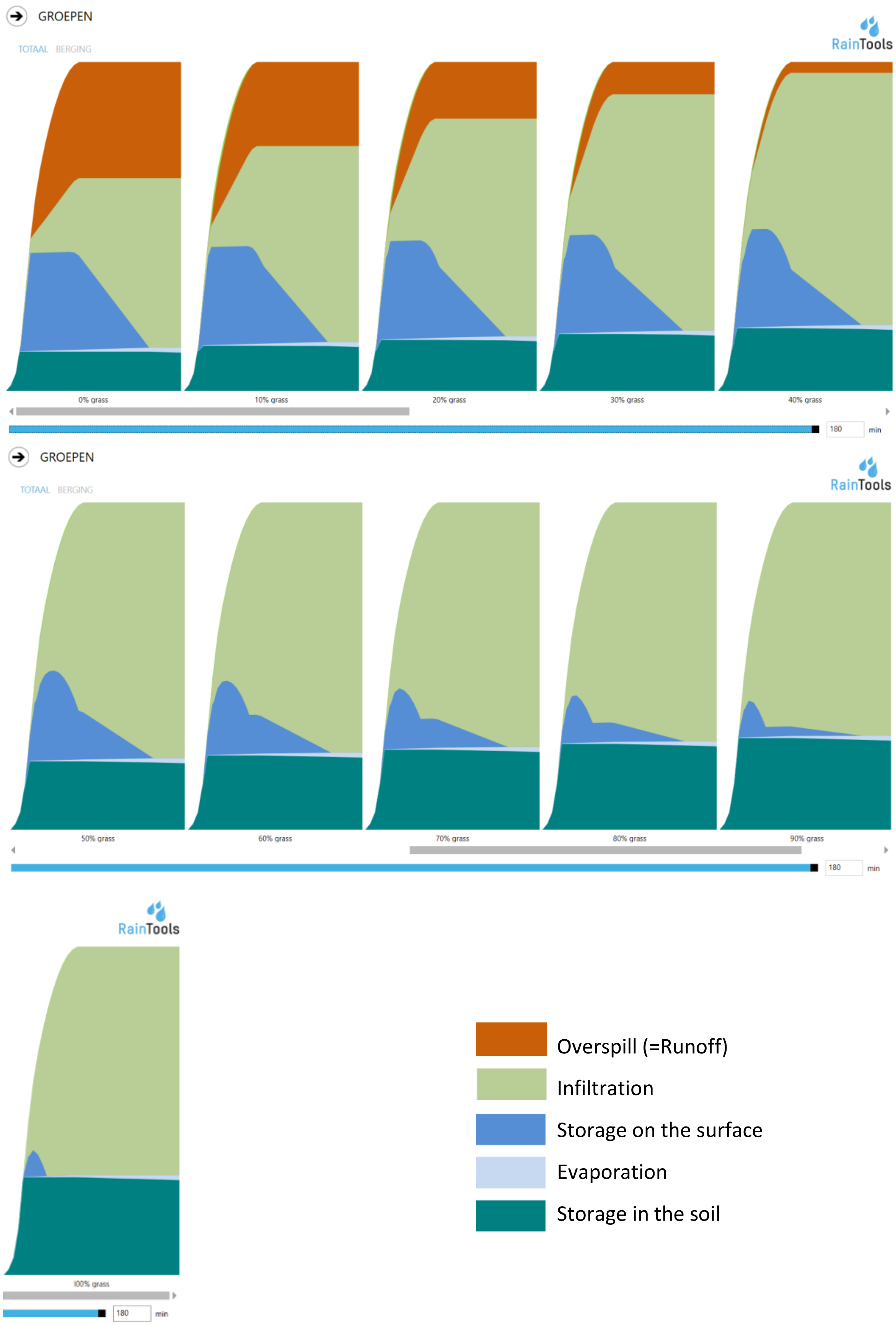


Figure 4 *Water balance of hypothetical gardens (consisting of 0-100% grass) over time (180 min) during precipitation event R05, showing the increase in infiltration & storage in the soil and the decrease in the runoff & storage on the surface when the greening of the gardens enhances.*

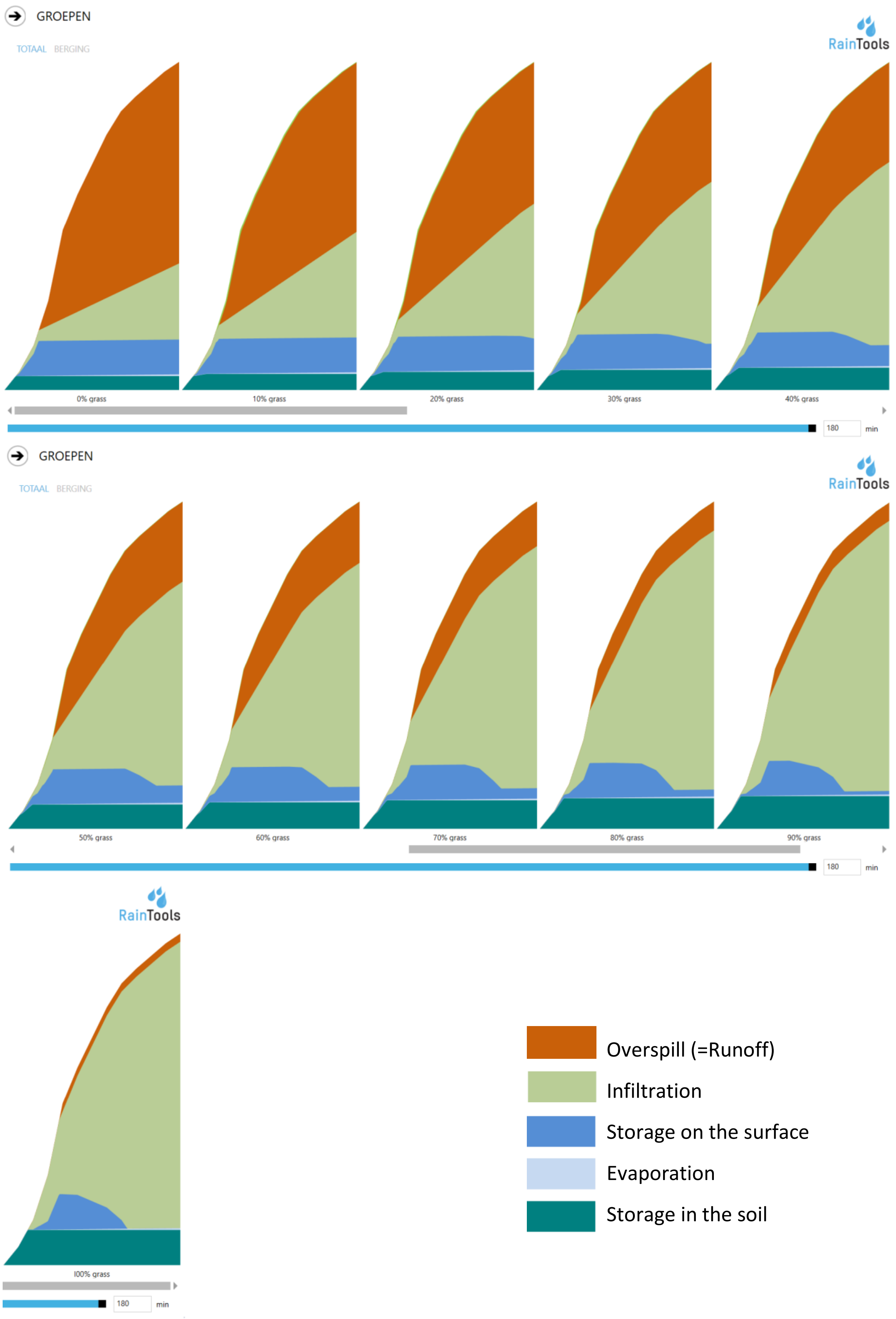


Figure 5 *Water balance of hypothetical gardens (consisting of 0-100% grass) in time (180 min) during precipitation event E03, showing the increase in infiltration & storage in the soil and the decrease in the runoff & storage on the surface when the greening of the gardens enhances.*

3.1.2 Precipitation series (2013)

The amount of runoff during the precipitation series for the eleven different gardens are listed in table 3. This table also includes the amounts of times that runoff occurs per year.
The runoff is highest for 0% grass area (completely paved) and lowest for 100% grass area. From 50 to 100% grass area no runoff occurs. The frequency of the runoff events per year is the highest for the 0% grass area. From 50 to 100% grass area the frequency is zero.

Table 3 *Amount and frequency of runoff from hypothetical gardens during 2013.*

Grass area (%)	0	10	20	30	40	50	60	70	80	90	100
Runoff (mm)	26.5	9.2	4.7	2.5	0.31	0.0	0.0	0.0	0.0	0.0	0.0
Frequency (per year)	4.0	3.0	1.0	1.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0

3.2 Spoorbuurt Garden

3.2.1 Precipitation events

Figure 6 & 7 show the output windows of the Wijktegel for the simulations of the Spoorbuurt garden during R05 and E03 respectively. The tables in these windows indicate the volume of water (m^3) for each term of the water balance for the different layers of the model. The grass (or 'unpaved') layers (#2 & #4) are the ones from which runoff occurs, in which #2 is part of the garden before the greening and #4 after. The graphs in these windows show the different terms of the water balance as a function of time for the garden before (32.1% grass) and after (36.6% grass) the greening.

During R05 the amount of runoff is 1.4 mm before the replacement and 0.93 mm after (34.9% decrease). The total infiltration increases from 12.3 mm to 12.6 mm. The other water balance terms show no apparent changes (Figure 6).
In case of E03, the runoff decreases from 16.5 mm to 15.3 mm (7.7%). The total infiltration increases from 24 mm to 25.3mm. Again, the other water balance terms do not change significantly (Figure 7).

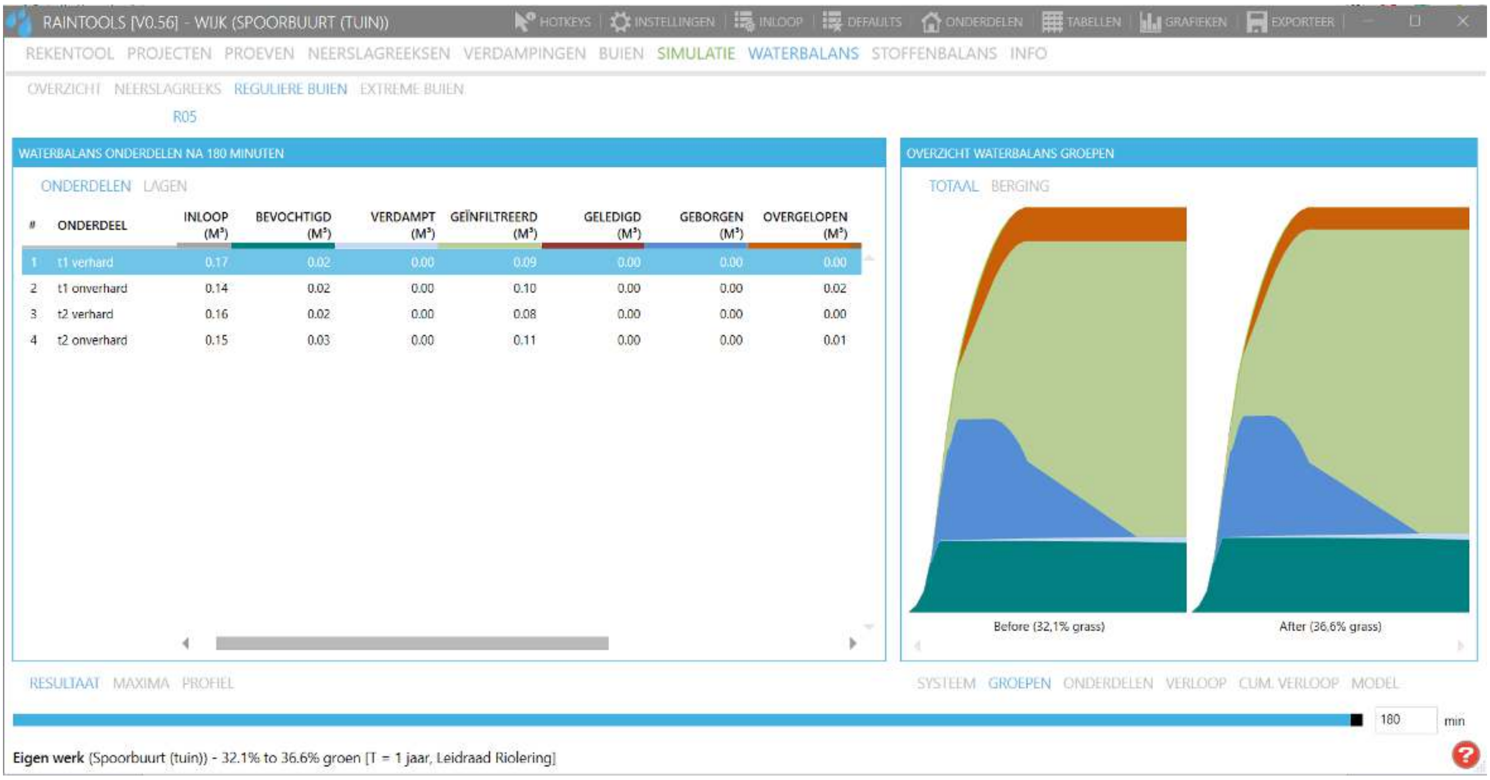


Figure 6 *Output window of the Wijktegel for a simulation of a garden in the Spoorbuurt district before and after the greening during E03. The graphs depict the different terms of the water balance table in respect to time (180min). The colours correspond to the terms in the table which also lists their volumes in m³ for each layer that is defined in the model.*

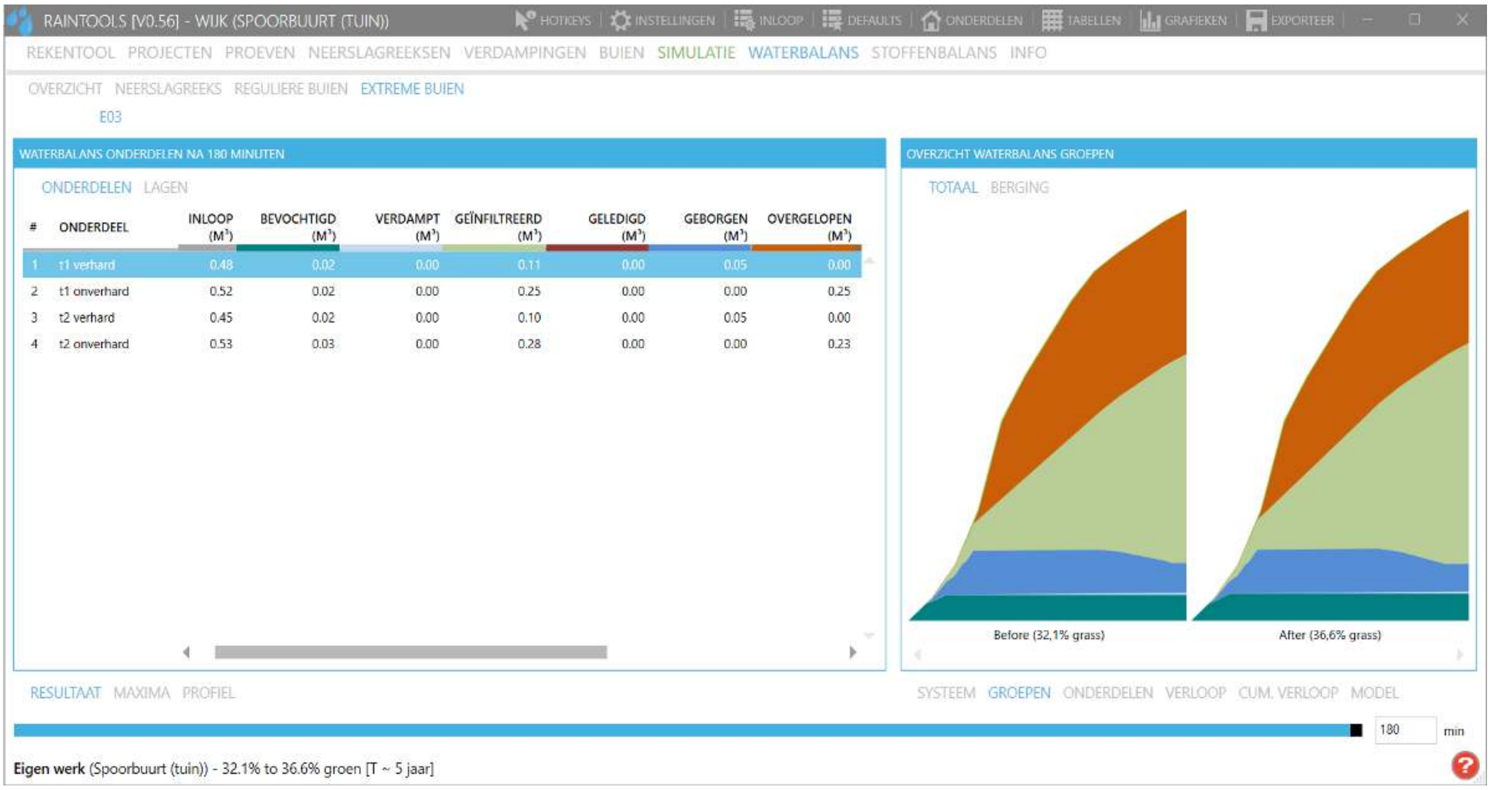


Figure 7 *Output window of the Wijktegel for a simulation of a garden in the Spoorbuurt district before and after the greening during E03. The graphs depict the different terms of the water balance table in respect to time (180min). The colours correspond to the terms in the table which also lists their volumes in m³ for each layer that is defined in the model.*

3.2.2 Precipitation Series

Figure 8 shows the output window of the Wijktegel for the simulation of the Spoorbuurt garden using the precipitation series of 2013. The table in this window indicates the volume of water (m^3) for each term of the water balance for the different layers of the model. The grass (or 'unpaved') layers (#2 & #4) are the ones from which runoff occurs, in which #2 is part of the garden before the greening and #4 after. The graph in this window shows the ratio of the different terms of the water balance for the garden before (32.1% grass) and after (36.6% grass) the greening.

During the precipitation series the runoff is 2.0 mm before the replacement and 1.1 mm after (48.1% decrease). The total infiltration decreases from 696.0 mm to 693.8 mm. The evaporation increases from 227.6 to 230.6 mm (Figure 8). The frequency of runoff events remains the same (once per year).

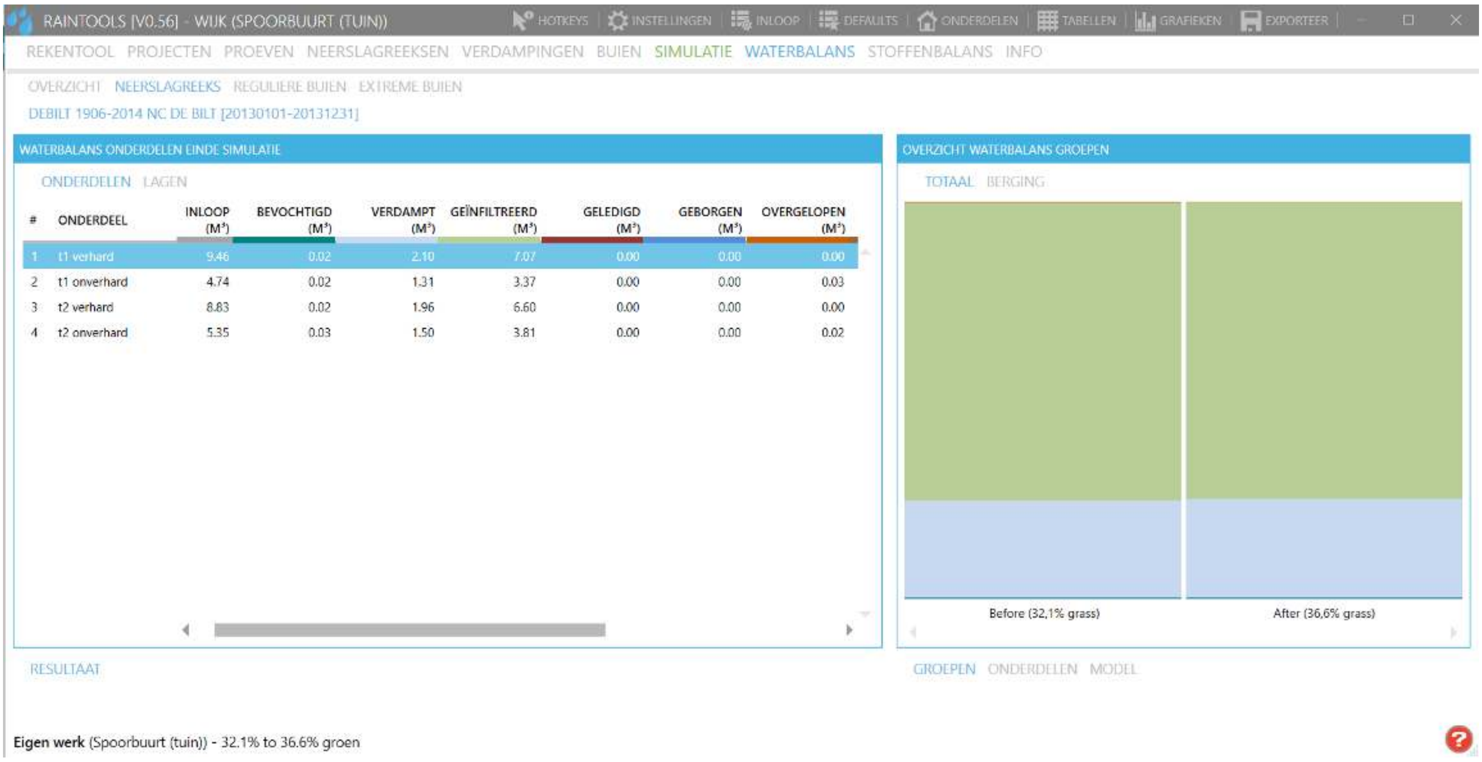


Figure 8 *Output window of the Wijktegel for a simulation of a garden in the Spoorbuurt district before and after the greening during 2013. The graphs depict the ratio of the different terms of the water balance. The colours correspond to the terms in the table which also lists their volumes in m^3 for each layer that is defined in the model.*

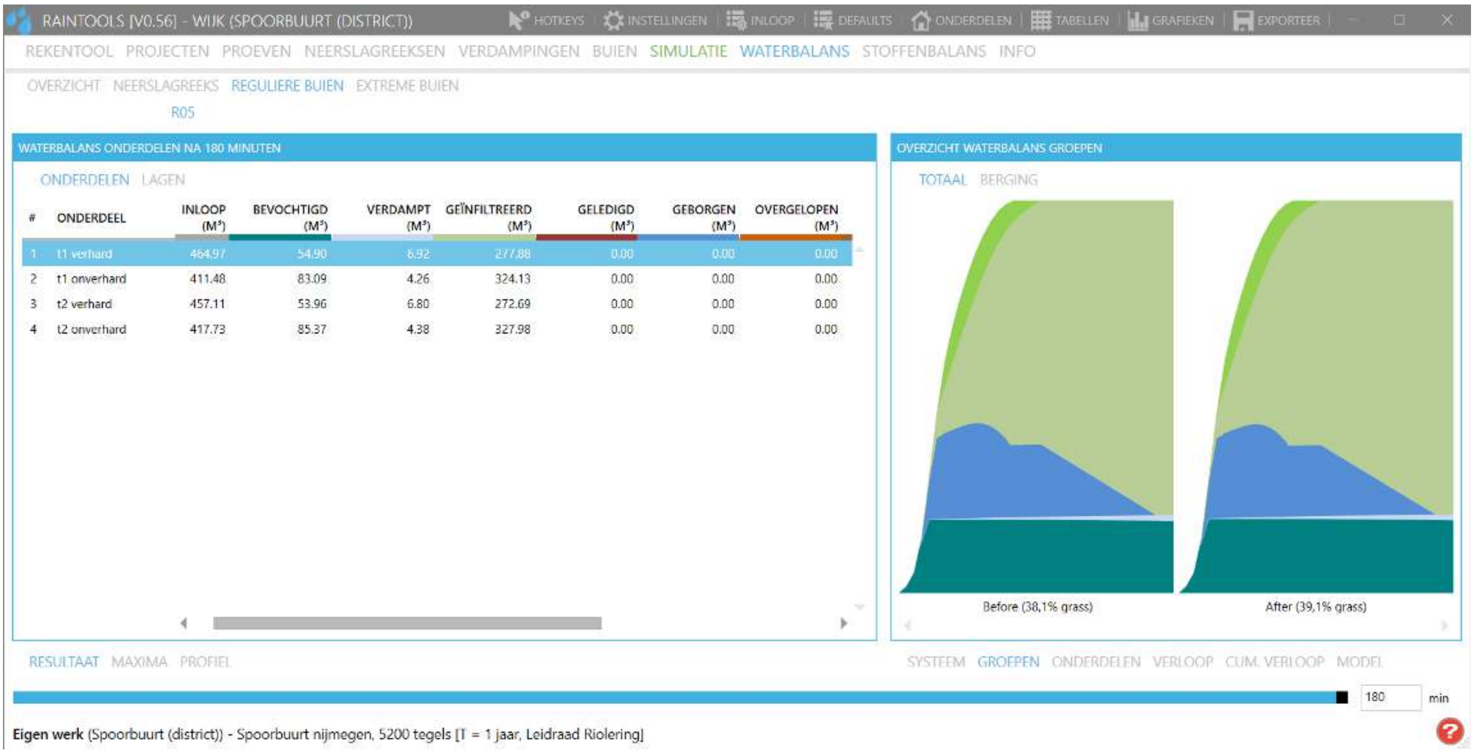
3.3 Spoorbuurt District

3.3.1 Precipitation events

Figure 9 & 10 show the output windows of the Wijktegel for the simulations of the Spoorbuurt district during R05 and E03 respectively. The tables in these windows indicate the volume of water (m^3) for each term of the water balance for the different layers of the model. The grass (or 'unpaved') layers (#2 & #4) are the ones from which runoff occurs, in which #2 represents part of the district before the greening and #4 after. The graphs in these windows show the different terms of the water balance as a function of time for the district before (38.1% grass) and after (39.1% grass) the greening.

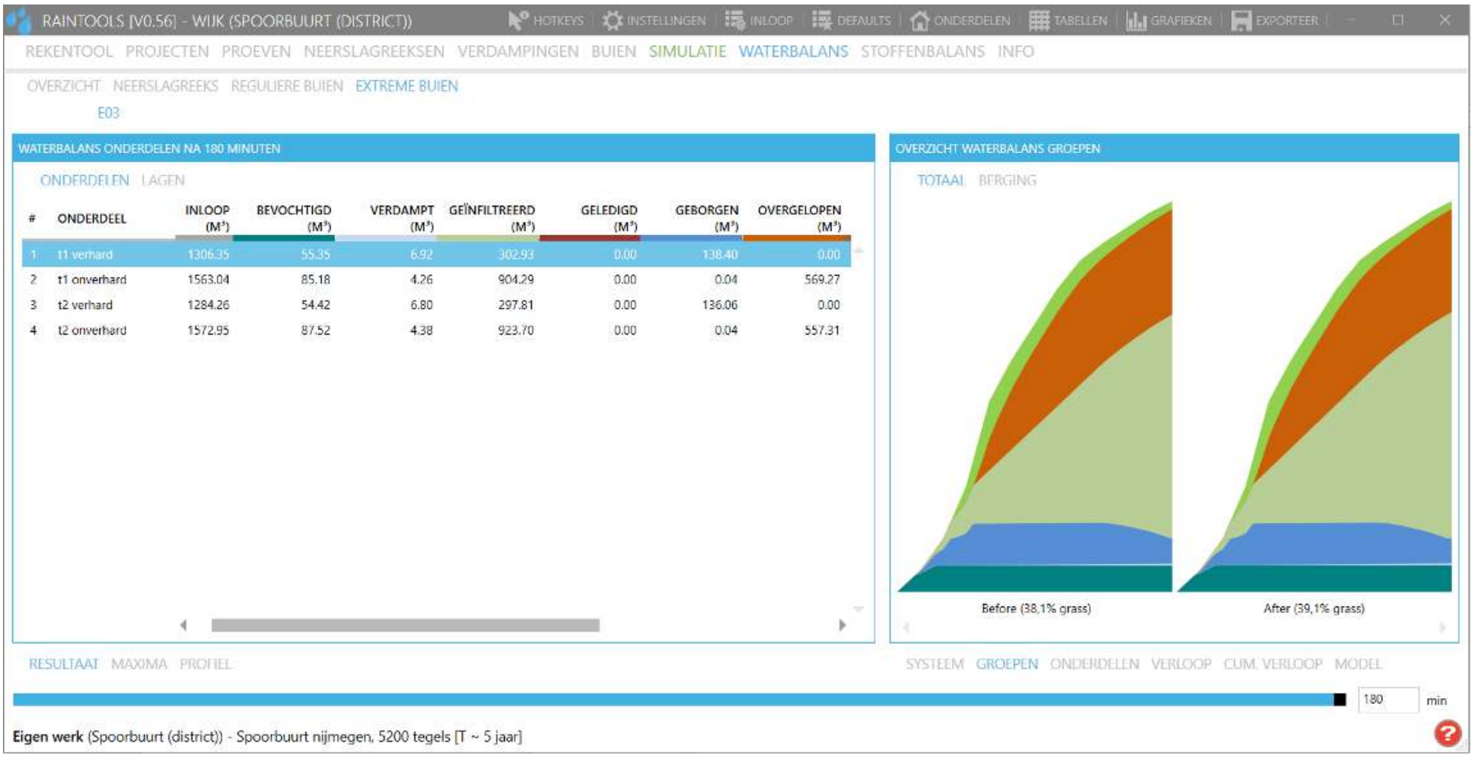
On the district scale the R05 event does not lead to any runoff in either scenario (before or after the 1% replacement). Also, in the other water balance terms there are no significant changes (Figure 9).

During the E03 event before the replacement the district has a runoff of 127.3 mm while after the replacement runoff is 124.6 mm (2.1% decrease). The changes in the other water balance terms are negligible (Figure 10).



#	ONDERDEEL	INLOOP (M³)	BEVOCHTIGD (M³)	VERDAMPT (M³)	GEÏNFILTREERD (M³)	GELEDIGD (M³)	GEBORGEN (M³)	OVERGELOPEN (M³)
1	t1 verhard	464.97	54.90	6.92	277.88	0.00	0.00	0.00
2	t1 onverhard	411.48	83.09	4.26	324.13	0.00	0.00	0.00
3	t2 verhard	457.11	53.96	6.80	272.69	0.00	0.00	0.00
4	t2 onverhard	417.73	85.37	4.38	327.98	0.00	0.00	0.00

Figure 9 *Output window of the Wijktegel for a simulation of the Spoorbuurt district before and after the greening during R05. The graphs depict the different terms of the water balance table in respect to time (180min). The colours correspond to the terms in the table which also lists their volumes in m^3 for each layer that is defined in the model.*



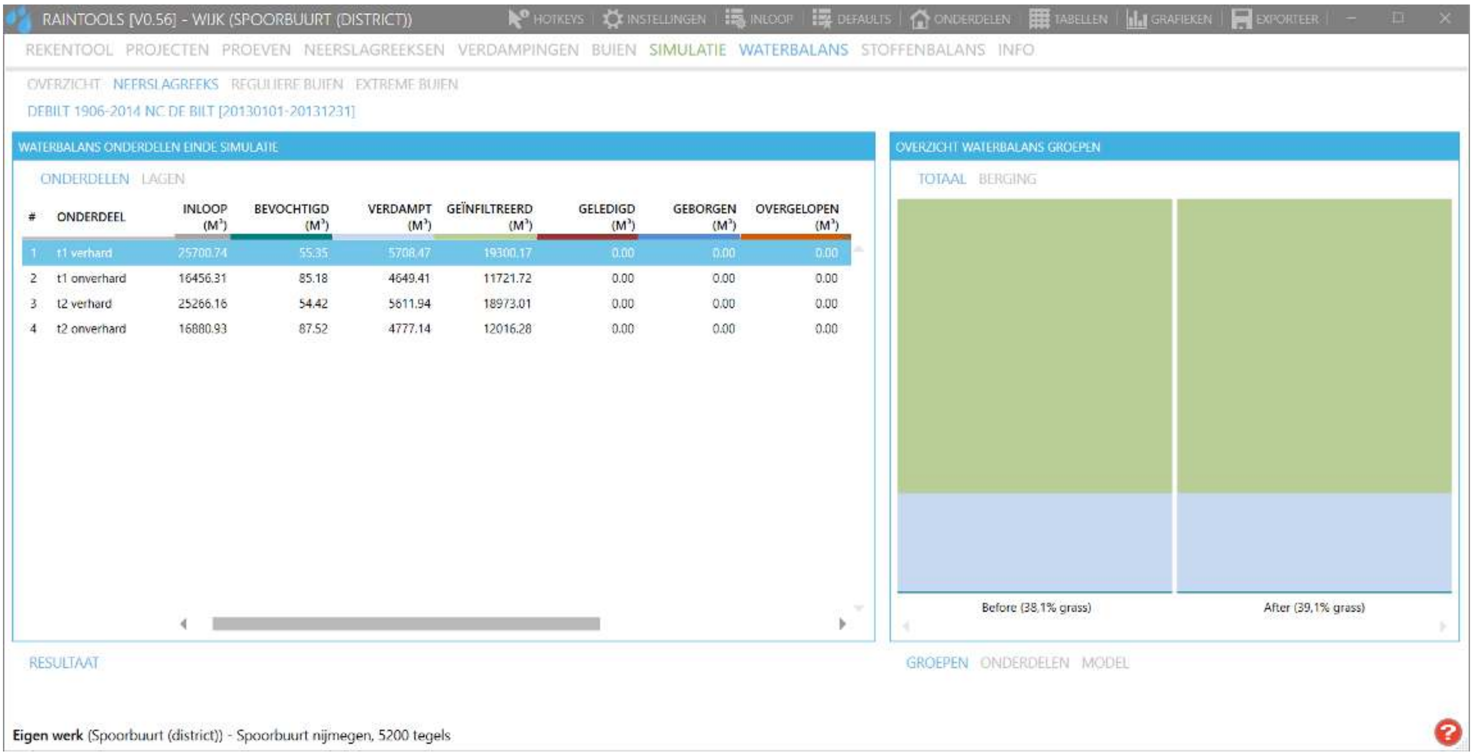
#	ONDERDEEL	INLOOP (M³)	BEVOCHTIGD (M³)	VERDAMPT (M³)	GEÏNFILTREERD (M³)	GELEDIGD (M³)	GEBORGEN (M³)	OVERGELOPEN (M³)
1	t1 verhard	1306.35	55.35	6.92	302.93	0.00	138.40	0.00
2	t1 onverhard	1563.04	85.18	4.26	904.29	0.00	0.04	569.27
3	t2 verhard	1284.26	54.42	6.80	297.81	0.00	136.06	0.00
4	t2 onverhard	1572.95	87.52	4.38	923.70	0.00	0.04	557.31

Figure 10 *Output window of the Wijktegel for a simulation of the Spoorbuurt district before and after the greening during E03. The graphs depict the different terms of the water balance table in respect to time (180min). The colours correspond to the terms in the table which also lists their volumes in m^3 for each layer that is defined in the model.*

3.3.2 Precipitation series

Figure 11 show the output window of the Wijktegel for the simulations of the Spoorbuurt district during R05 and E03 respectively. The table in this windows indicates the volume of water (m^3) for each term of the water balance for the different layers of the model. The grass (or 'unpaved') layers (#2 & #4) are the ones from which runoff occurs, in which #2 represents part of the district before the greening and #4 after. The graph in this window shows the ratio of the different terms of the water balance for the district before (38.1% grass) and after (39.1% grass) the greening.

No runoff occurs in the district when using the precipitation series. Similar to the precipitation events, there are no significant changes in the other water balance terms (Figure 11).



#	ONDERDEEL	INLOOP (M³)	BEVOCHTIGD (M³)	VERDAMPT (M³)	GEÏNFILTREERD (M³)	GELEDIGD (M³)	GEBORGEN (M³)	OVERGELOPEN (M³)
1	t1 verhard	25700.74	55.35	5708.47	19300.17	0.00	0.00	0.00
2	t1 onverhard	16456.31	85.18	4649.41	11721.72	0.00	0.00	0.00
3	t2 verhard	25266.16	54.42	5611.94	18973.01	0.00	0.00	0.00
4	t2 onverhard	16880.93	87.52	4777.14	12016.28	0.00	0.00	0.00

Figure 11 *Output window of the Wijktegel for a simulation of the Spoorbuurt district before and after the greening during 2013. The graphs depict the ratio of the different terms of the water balance table. The colours correspond to the terms in the table which also lists their volumes in m^3 for each layer that is defined in the model.*

4. Discussion

4.1 Hypothetical gardens

Per 1% greening the runoff decreases on average by 0.14 mm during R05 and by 0.35 mm during E03. Relatively this means a runoff decrease of 2.5% and 1.2% per 1% greening for R05 and E03 respectively. The decrease in runoff and water storage on the surface can be explained by the increase in infiltration and water storage in the soil that occurs when more garden tiles are replaced by grass. The precipitation that would normally be discharged has more chance to infiltrate and get stored in the soil. This leads to a lower runoff and water storage on the surface.

The precipitation of E03 is too intense for even a 100% grass surface to infiltrate and store all the water. For this reason, there is still 1.2 mm discharging from this garden during this event.
At a 10% replacement of a completely paved garden the frequency of runoff events drops only slightly. The total amount of discharge, on the contrary, is substantially reduced (65.25%). This means that the runoff events do not become considerably less frequent, but they do become less intense.
The fact that only the precipitation series of the year 2013 has been researched should be taken into account here. The results from this specific year are not necessarily representative for other years. It was simply used because it was the most recent annual data that was available. There was not enough time to simulate more years.

4.2 Spoorbuurt gardens

During R05 and E03 the runoff decreased by 0.46 and 1.3 mm while the infiltration increased by 0.33 and 1.3 mm respectively. The decrease in runoff is explained for the largest part (71.4%) or completely by the increase in the infiltrated amount. In case of R05 the remaining 0.13 mm are probably stored in the ground or evaporated from the surface.

The precipitation series led to different results however, as runoff decreased by 0.93 mm, but the infiltration also decreased by 2.2 mm. This decrease in infiltration is most likely caused by the 3 mm increase in evaporation. This increase in evaporation is only noticeable for a long-term situation. During a precipitation event this term is often negligible. Out of the 3 mm that leaves the system by evaporation, 2.2 mm can be attributed to the infiltration decrease and the other 0.8 mm are linked to the decrease in runoff. This means that 0.13 mm out of the 0.93 mm of runoff reductions are left. These amounts can be allocated to the small increases in water storage terms.

Comparing two precipitation events with similar return periods can result in quite different outcomes. Despite having the same duration and rain intensity, one can see that the difference between the normal situation and the replaced situation is a lot less apparent in the R06 (Appendix A16) situation than in the R05 situation (Figure 6). Besides there being more runoff in case of R06, the reduction caused by the replacement is only 13.5%. This is a lot less than the 34.9% reduction that occurs during the R05 event. The most likely cause of this is the different timing of the peak of both events. R05 has the peak in the beginning of the event while R06 has the peak at the end. For R05 this means that most of the precipitation falls early on and has the time to infiltrate in a relatively unsaturated soil. This leads to less water being available for runoff. R06, on the other hand, starts off with a low amount of precipitation that gradually saturates the soil. Once the peak occurs the saturated soil cause the infiltration process to be slower, resulting in a high runoff.

4.3 Spoorbuurt district

Model results suggest that in the Spoorbuurt the 1% greening was too small to cause significant changes in the water balance during R05 or the precipitation series. At the large scale the 1% replacement only lead to changes in case of extreme situations such as E03. In that case the runoff decreases by 2.1%.

4.4 Accuracy of results

It is important to realize that the simulations are based on strongly simplified situations. Both the district and the gardens consisted of only two separate layers. For the district this meant that it was considered as one big unit instead of a diverse system of gardens, houses and public areas. By doing so, the paved and unpaved spatial configuration was left out of the calculation in both situations. Within the district there could therefore possibly be significant local differences that are not evident because of the simplified conditions. At first an attempt was made to realize more detailed situations, but they lead to inaccurate results. It required too many input variables such as roof size, sewer connections, and routing of different layers too accomplish realistic results. The simplifications presented here eventually made the research feasible in the available time.

What also needs to considered is that the model is not checked against observations. The assumptions of the model are therefore difficult to validate. For example, the area that represented the replaced garden tiles was considered to consist fully of grass. This assumption made it possible to use the same values throughout the replaced surface areas, but it is not very realistic. This would improve if bare areas and other vegetation types would be accounted for. Moreover, all the paved areas were assumed to consist of 'standard garden tiles' with a dimension of 30 x 30 cm (= 0.09 m^2) (Bebelaar and Bakker, 1981). This assumption made it possible to use the same values for all paved surface areas. Multiple types and sizes of paved layers will be present in reality. These have all different infiltration rates that should be taken considered.

In the dataset from the Spoorbuurt district the areas which were not classified as 'green' were all considered to be paved. This assumption is not justified because part of the area was actually classified as 'unknown' by the municipality of Nijmegen. By choosing to generalise all this as paved, the percentage of paved area changed from 31.4% to 61.9%. Next to that, the percentages of the different surface types were taken from a dataset of Hengstdal. Spoorbuurt is only a small part of Hengstdal and therefore does not necessarily have the same percentages of surface types.

The choice for the total area in the garden scenario was based on field research in Wageningen. It might therefore not be representative for gardens in other areas. Moreover, this research was limited to 'standard' front gardens and is not representative for a complete plot (including back garden) since these are often much larger.

In reality the ground level is not always even as is assumed in the model. A difference in the ground level between the paved and the grass layers would mean a different storage time on the surfaces. This leads to differences in, amongst other, the infiltration and evaporation rates. As a result, the runoff is affected as well. Accurately measuring the ground levels of the specific areas will therefore prevent biases in the runoff.

The evaporation factor is assumed to be 1 for both grass and garden tiles. Although this might be correct for a short-term trajectory, for a longer simulation period more accurate values are needed.

5. Conclusions and recommendations

The precipitation event R05 was of high enough intensity to result in runoff in at least five of the hypothetical gardens while still being considered as a relatively common event. It was therefore deemed useful for analysing the effects of different degrees of greening. E03 had a longer duration and larger magnitude which helped studying the effects on the runoff during more extreme events.
How the runoff from front gardens and districts is affected by the replacement actions of e.g. Operatie Steenbreek but also by hypothetical greening could be carefully modelled with RainTools, producing the following results:

Modelling of hypothetical gardens showed that per 1% greening, the runoff decreases on average by 0.14 mm (2.5%) during a precipitation event with a return period of a year (R05). During a more extreme event with a return period of 5 years (E03) the runoff decreased by about 0.35 mm (1.2%) per 1% greening.
A 10% replacement leads to less intensive runoff events during the annual precipitation series of 2013. Zero runoff during this year is achieved when a garden consists for 50% of grass.

Simulating the 1% greening in the Spoorbuurt district shows a runoff reduction of 2,1% during event E03. There are no changes in the runoff regarding both R05 and the precipitation series. This was because there was no runoff occurring in both situations.

In an average front garden in de Spoorbuurt, a realistic 4.5% increase in grass area resulted in a 34.9% decrease in runoff in case of the R05. The runoff decreased by 7.7% during E03. Throughout the annual precipitation series, the greening caused the runoff to decrease by 48.1% and the frequency of runoff events remained once per year.

To conclude, this research showed that when garden tiles are replaced by grass, the runoff decreases based on the type of precipitation event and the extent of replacement. The conclusions of this research are however based on a strongly simplified model and should be regarded as indicative.

Further research that explores a more detailed model should be conducted to see if more realistic simulations are feasible. In addition, testing the model with a real-life situation from which the water balance terms are known in detail will help to verify the model's accuracy. Lastly, it is recommended to make a cost-benefit analysis of the greening of paved areas. This could be useful for determining if the greening of paved areas is less costly than paying for the extra measures/damages that the higher runoff causes.

References

Broks, K., & Luijtelaar, H. (2015). Groene daken nader beschouwd: over de effecten van begroeide daken in breed perspectief met de nadruk op de stedelijke waterhuishouding. Stichting Toegepast Onderzoek Waterbeheer.

Cornelissen, E. (2018). *Operatie Steenbreek – Tegel eruit, plant erin. Help Den Haag vergroenen en ontstenen*. Retrieved from https://duurzaamdenhaag.nl/projecten/operatiesteenbreek

De Groene Campus, (2015). *Aan de slag.* Retrieved from https://maken.wikiwijs.nl/bestanden/421188/bestraten%20A%20les%204.pdf

Geys, J. F. (1988). Water als minerale grondstof. GEA, 21(4), 100-103.

Haase, D. (2009). Effects of urbanisation on the water balance–A long-term trajectory. Environmental impact assessment review, 29(4), 211-219.

Leidraad riolering (2004). Module C2100 Rioleringsberekeningen, hydraulisch functioneren.

London Assembly Environment Committee (2005). Crazy Paving: The Environmental Importance of London's Front Gardens. London.

Luijtelaar, H., & RIONED, S. (2015). Regenwatersystemen op de testbank: benchmark functioneren bij extreme neerslag. Stichting RIONED.

Natale, L., & Savi, F. (2007). Monte Carlo analysis of probability of inundation of Rome. Environmental Modelling & Software, 22(10), 1409-1416.

Pachauri, R. K., & Reisinger, A. (2007). IPCC fourth assessment report. IPCC, Geneva, 2007.

Perry, T., & Nawaz, R. (2008). An investigation into the extent and impacts of hard surfacing of domestic gardens in an area of Leeds, United Kingdom. Landscape and Urban Planning, 86(1), 1-13.

Scalenghe, R., & Marsan, F. A. (2009). The anthropogenic sealing of soils in urban areas. Landscape and urban planning, 90(1-2), 1-10.

Smits, I., Wijngaard, J. B., Versteeg, R. P., & Kok, M. (2004). Statistiek van extreme neerslag in Nederland. STOWA, Utrecht.

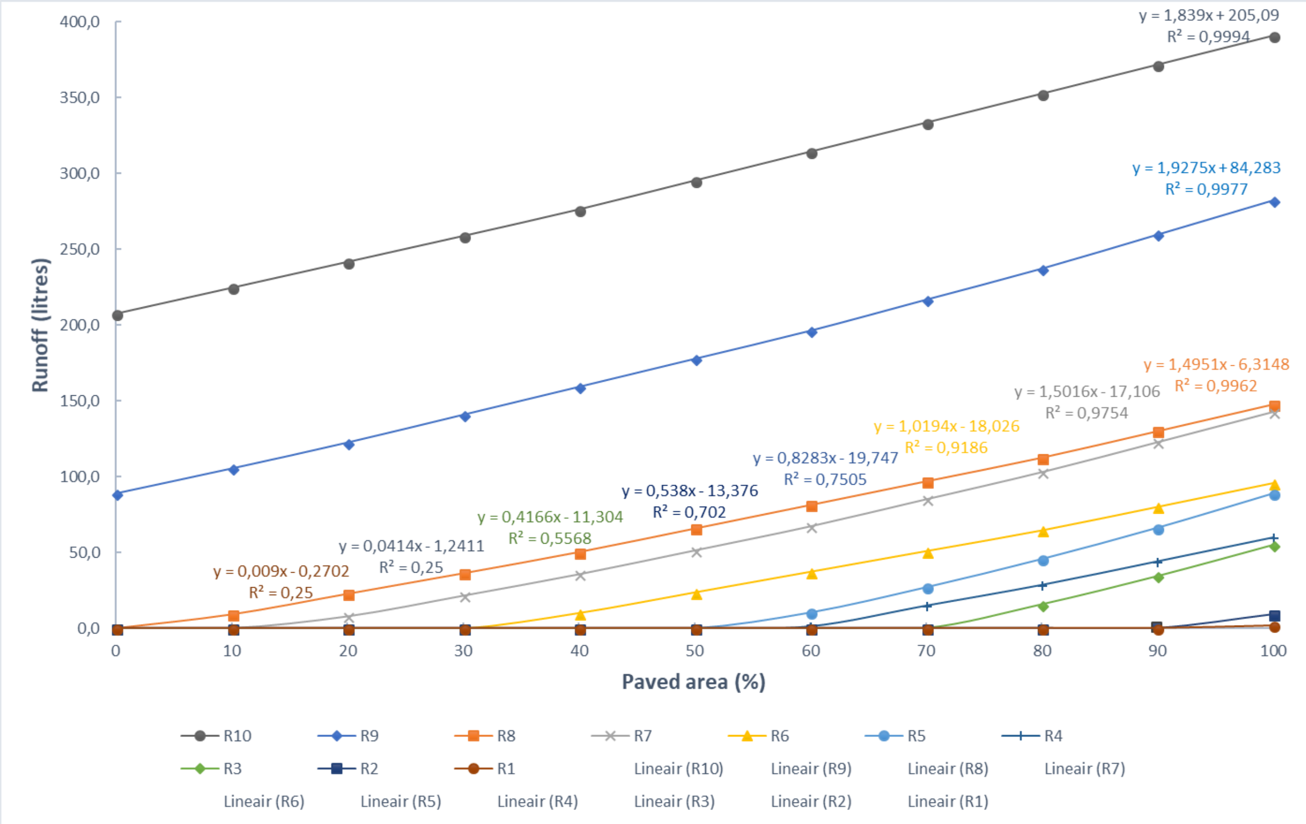
United States Department of Agriculture (1986). Urban Hydrology for Small Watersheds: TR-55.

Verbeeck, K., Van Orshoven, J., & Hermy, M. (2011). Measuring extent, location and change of imperviousness in urban domestic gardens in collective housing projects. Landscape and urban planning, 100(1-2), 57-66.

Zwaagstra, C. (2014). The contribution of soil sealing in urban private gardens to runoff and urban heating. University of Groningen.

www.riool.net (Stichting RIONED)

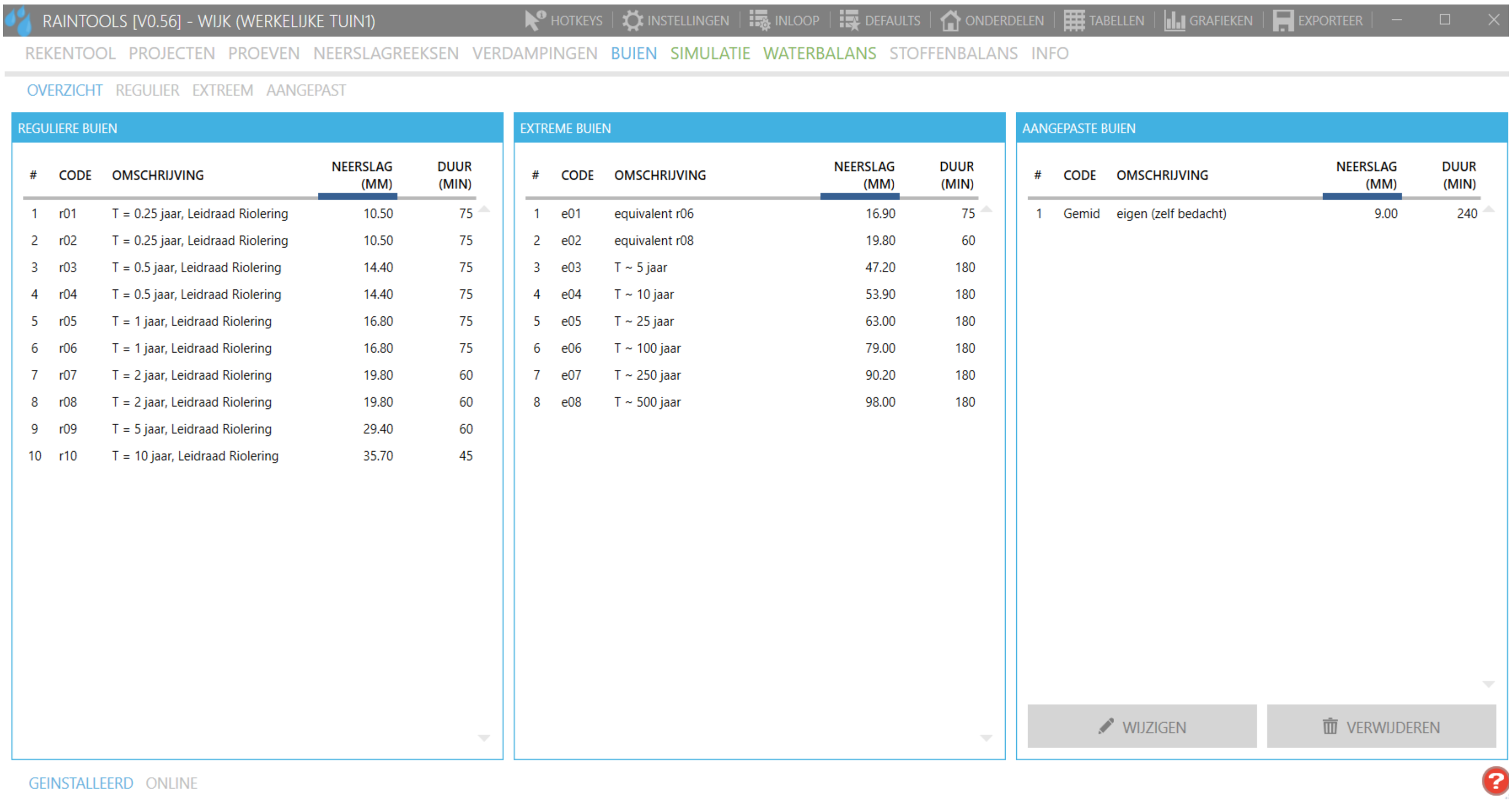
Appendix



A1 *Runoff (litres) as a function of paved area (%) after 180min for the precipitation events R01-R10, showing for each event an increase in runoff when the percentage of paved area increases. Results from the Perceeltegel tool in RainTools.*

	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10
Paved area %										
100	2,0	9,1	54,8	59,7	88,9	95,7	143,0	147,8	282,5	390,8
90	0,0	0,0	34,3	44,0	66,3	80,0	122,9	130,1	259,8	371,7
80	0,0	0,0	15,7	28,6	45,7	64,6	103,1	112,6	237,4	352,6
70	0,0	0,0	0,0	15,0	27,0	50,9	85,2	97,0	216,8	333,5
60	0,0	0,0	0,0	1,5	10,5	37,3	67,3	81,3	196,3	314,4
50	0,0	0,0	0,0	0,0	0,0	23,7	51,4	65,8	177,7	295,3
40	0,0	0,0	0,0	0,0	0,0	10,1	35,6	50,3	159,2	276,3
30	0,0	0,0	0,0	0,0	0,0	0,0	21,4	36,3	140,8	258,8
20	0,0	0,0	0,0	0,0	0,0	0,0	7,8	22,7	122,5	241,8
10	0,0	0,0	0,0	0,0	0,0	0,0	0,0	9,1	105,3	224,7
0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	88,8	207,7

A2 *Runoff (litres) caused by the precipitation events R01-R10 on the hypothetical gardens with their paved area (100-0%). Results from the Perceeltegel tool in RainTools.*



***A3** Precipitation events overview window in the Wijktegel tool from Raintools, showing the precipitation events from the Leidraad Riolering with their return periods, magnitude and duration. Also visible is the custom created precipitation event.*

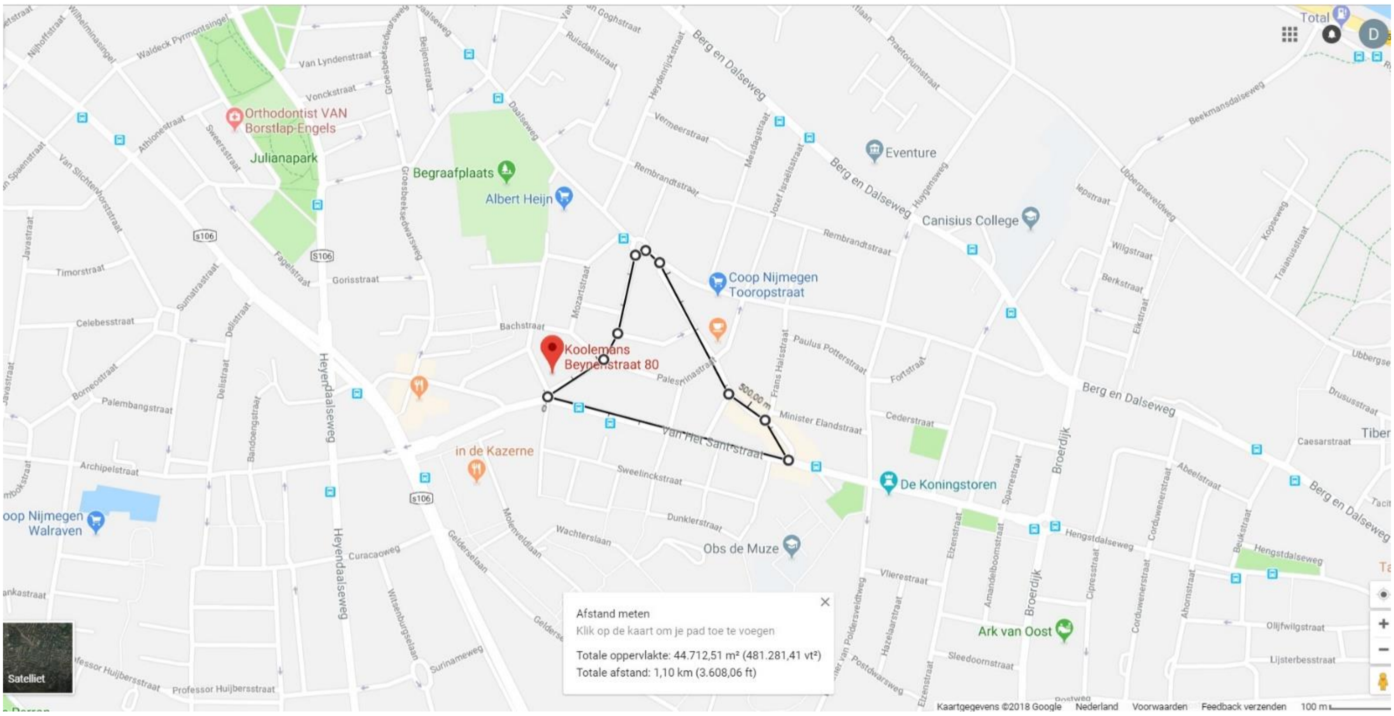
***A4**. Description and values of the input variables of the top layers in the Wijktegel tool from RainTools.*

Input variable	Description	Value	Unit
Surface area	The area of each individual surface type	Single gardens: 15 (total area) District: 44,713 (total area)	m^2
The ground level	The elevation of the surface compared to sea level	0	mm
The water on street level	The height of the water column that is allowed to be on the surface	0.1	m
Water storage in the soil	The height of the water column that is stored in the soil	Paved areas: 2 Grass areas : 5	mm
Water storage on the surface	The height of the water column that is stored on the surface	5	mm
Infiltration rate	The amount of water that infiltrates into the ground every hour	Paved areas: 3.9 Grass areas: 20.8	mm/h
Evaporation factor	The relative evaporation magnitude of the surface type in comparison to a grass land	1	-
Overflow length	The width of the water exchange plane between two different surfaces	Single gardens: 3,000 District: 200,000	mm

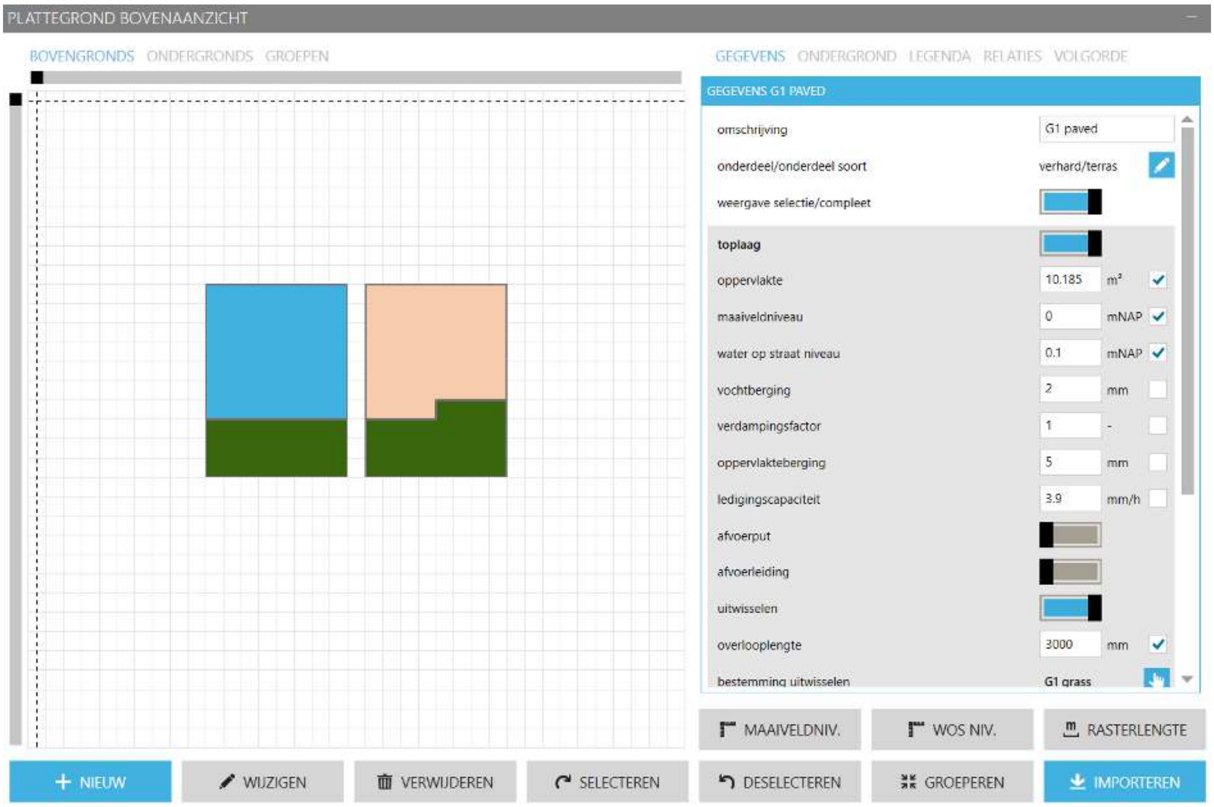
A5 Input variables of the sublayers in the Wijktegel tool from RainTools.

Input variable	Description	Value	Unit
Layer thickness	The thickness of the subsoil	200	mm
Porosity	The fraction of the volume of empty spaces over the total volume of the subsoil	0.35	-
Permeability	The speed with which water passes through the subsoil	1000	mm/d

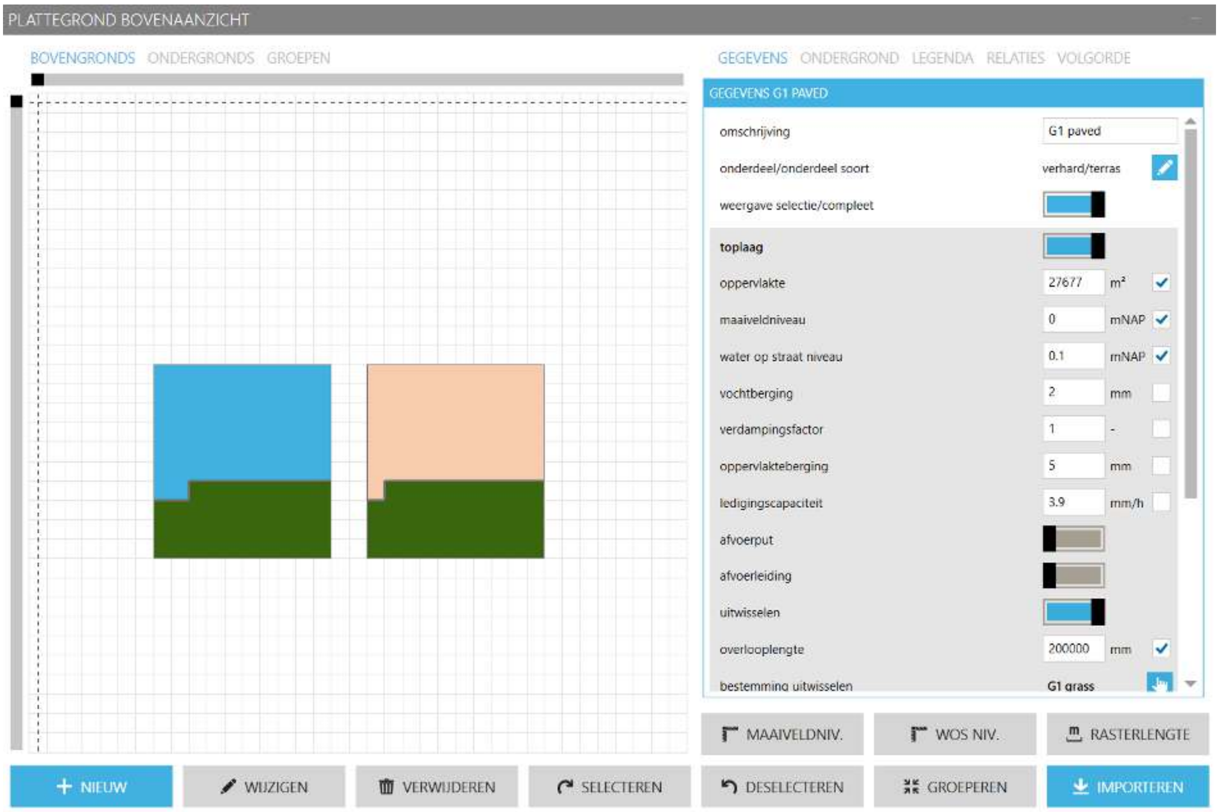
A6 Front gardens with garden tiles in residential areas of Wageningen.



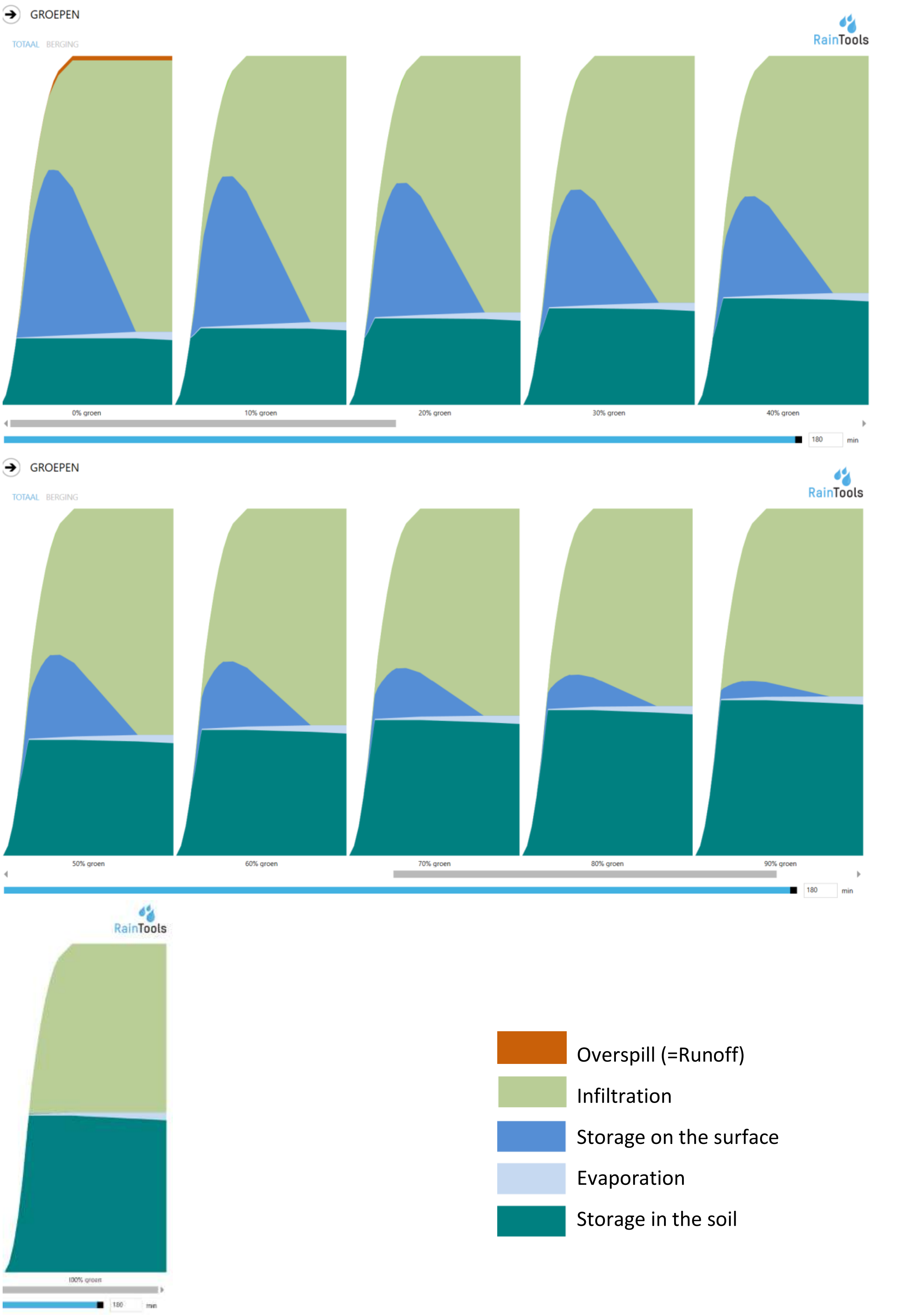
A7 Map of the Spoorbuurt district and its surroundings. Retrieved from www.google.nl/maps



A8 *Top view window of the Spoorbuurt garden scenario in the Wijktegel tool from RainTools, , showing the spatial configuration of the different surface layers and the input variables for the selected layer G1 paved (blue).*

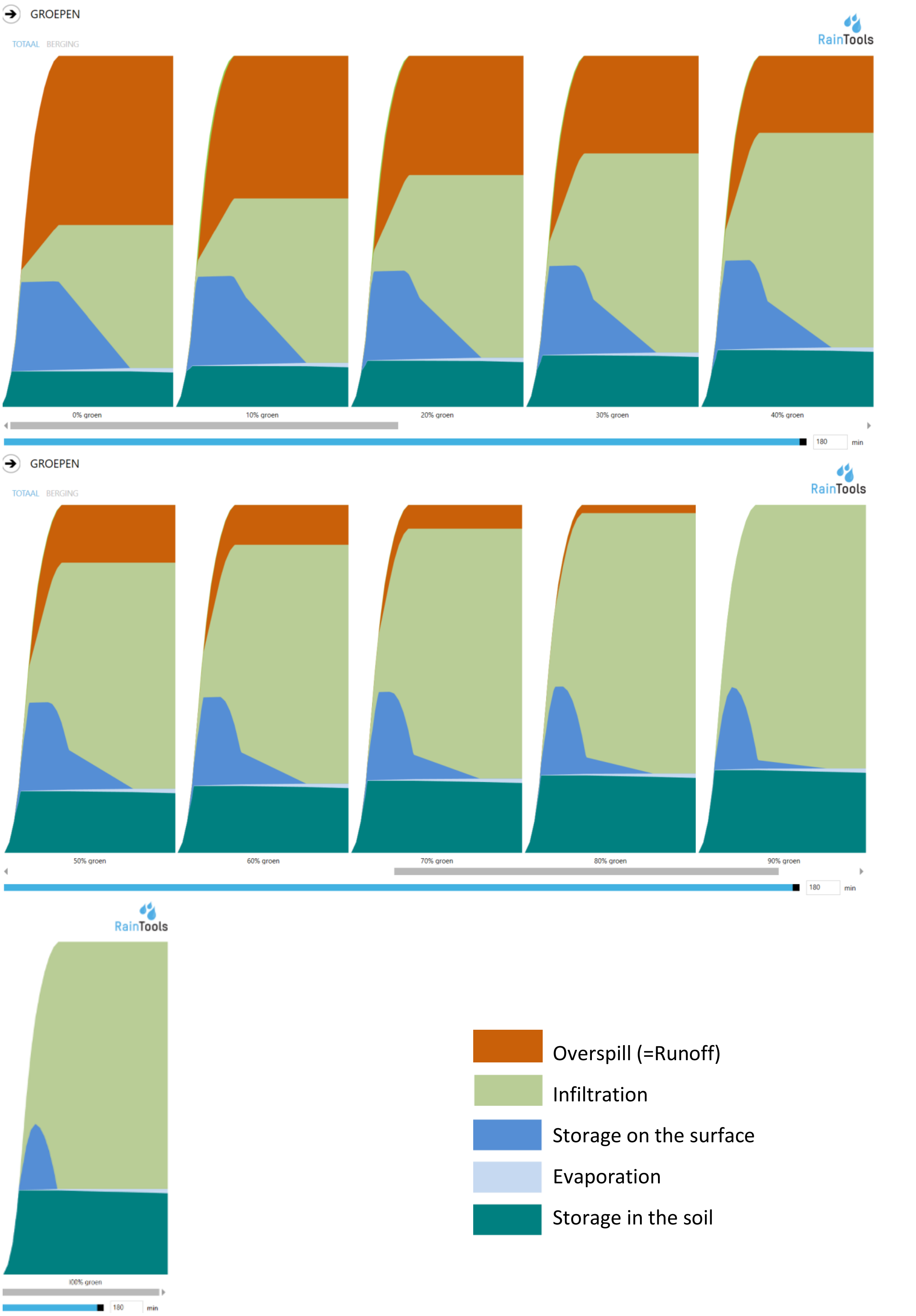


A9 *Top view window of the Spoorbuurt district scenario in the Wijktegel tool from RainTools, showing the spatial configuration of the different surface layers and the input variables for the selected layer G1 paved (blue).*

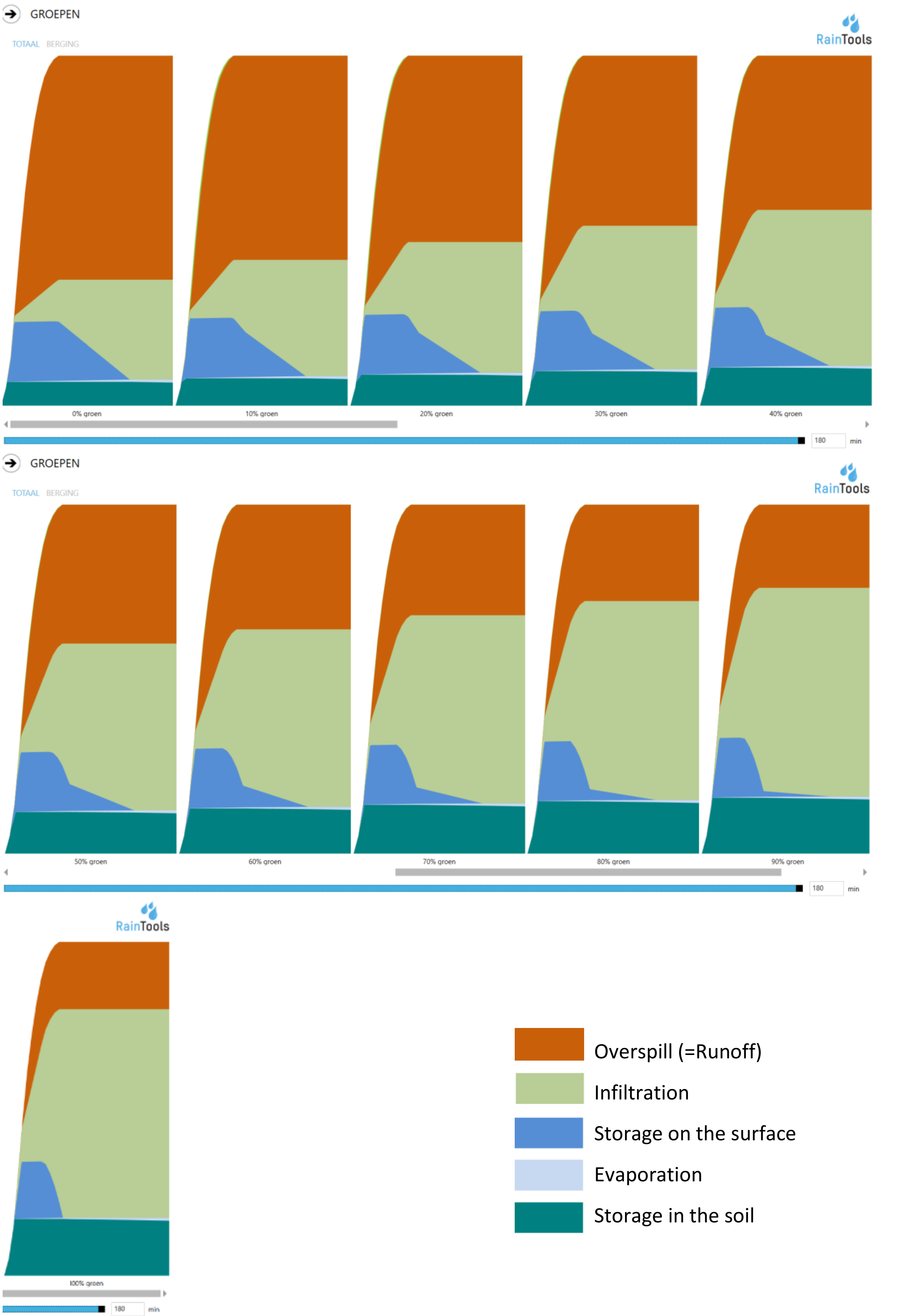


***A10** Water balance of hypothetical gardens (consisting of 0-100% grass) in time (180 min) during precipitation event R01, showing the increase in infiltration & storage in the soil and the decrease in the runoff & storage on the surface when the greening of the gardens enhances.*

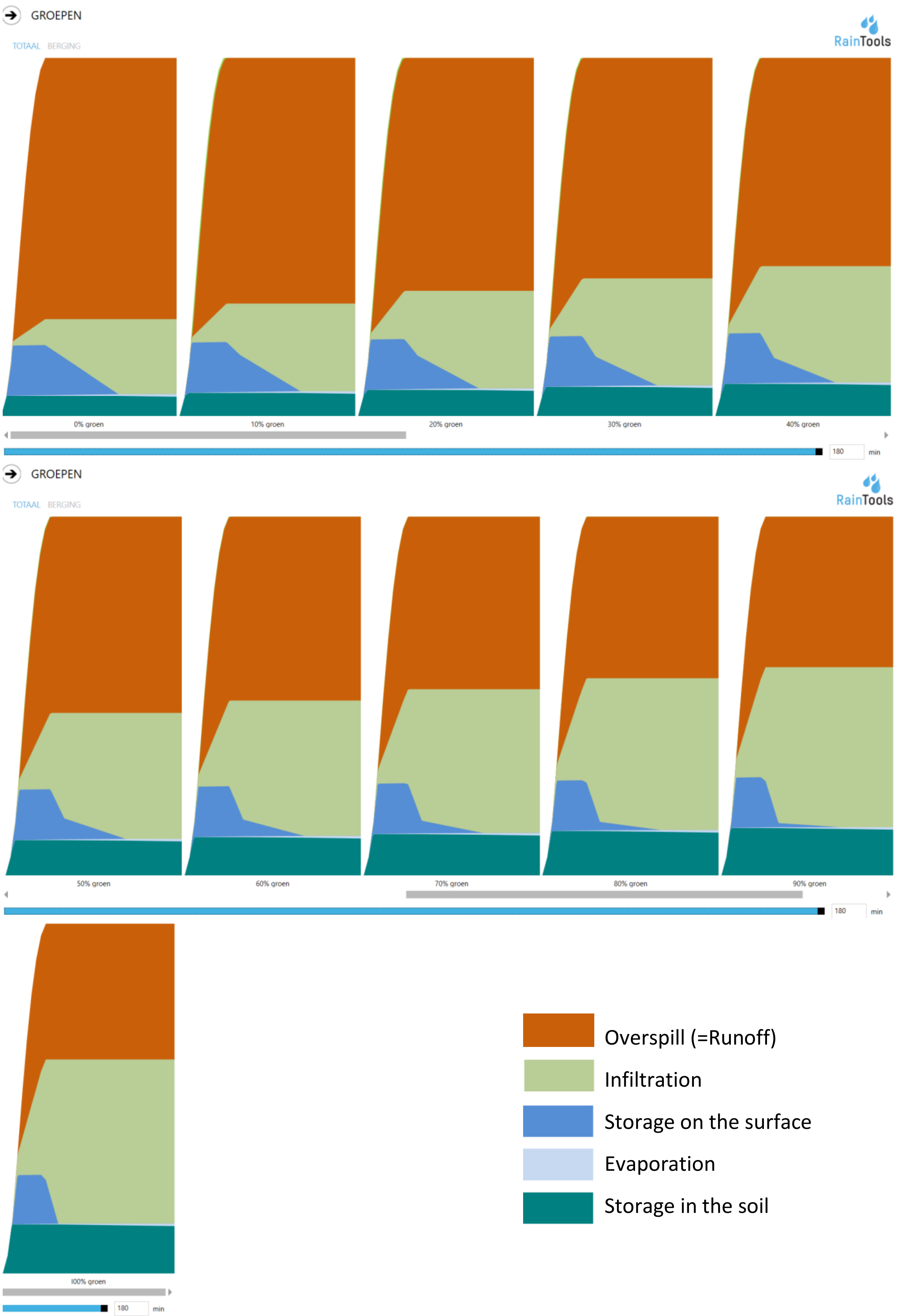
A11 *Water balance of hypothetical gardens (consisting of 0-100% grass) in time (180 min) during precipitation event R03, showing the increase in infiltration & storage in the soil and the decrease in the runoff & storage on the surface when the greening of the gardens enhances.*



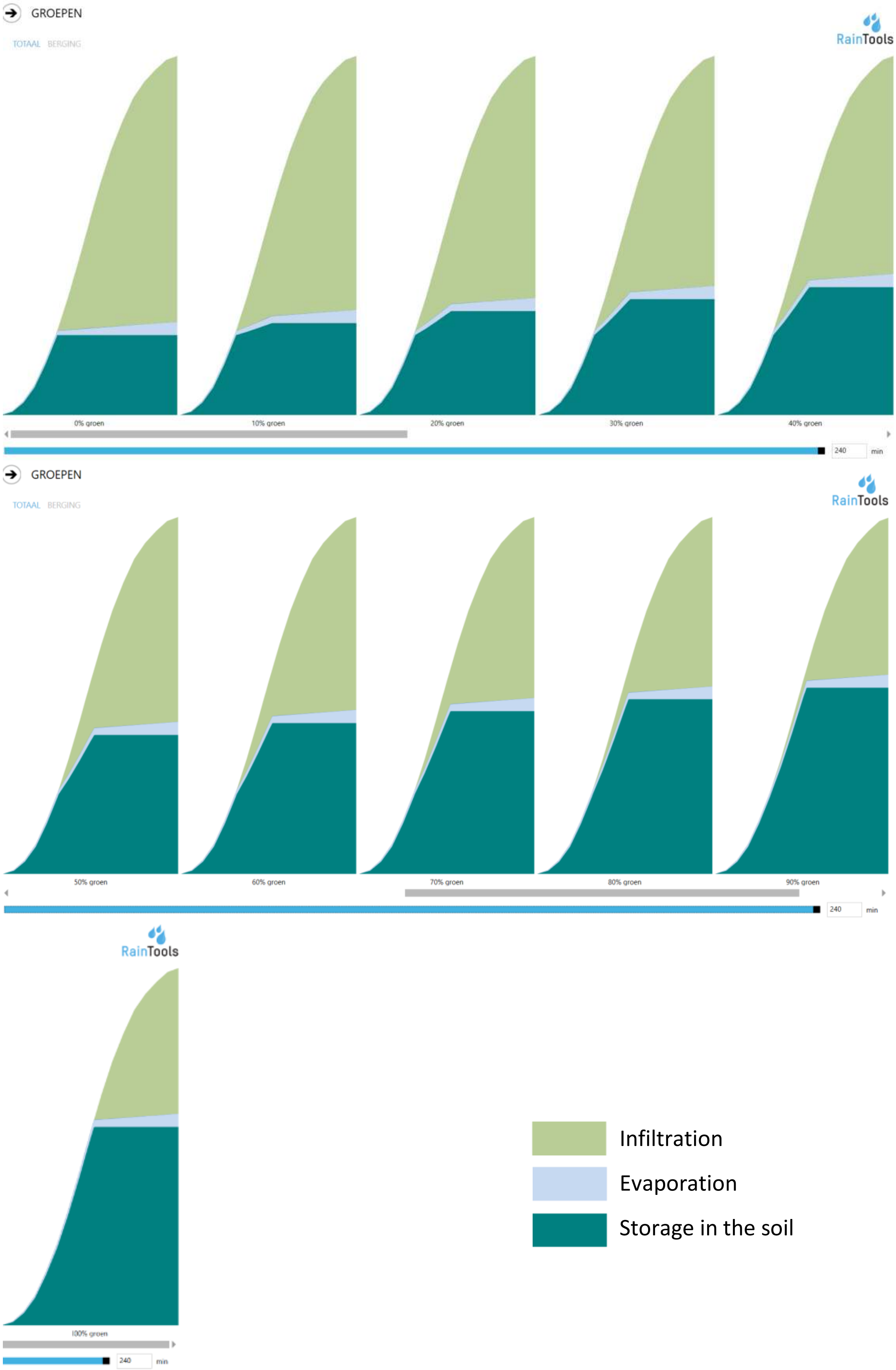
A12 *Water balance of hypothetical gardens (consisting of 0-100% grass) in time (180 min) during precipitation event R07, showing the increase in infiltration & storage in the soil and the decrease in the runoff & storage on the surface when the greening of the gardens enhances.*



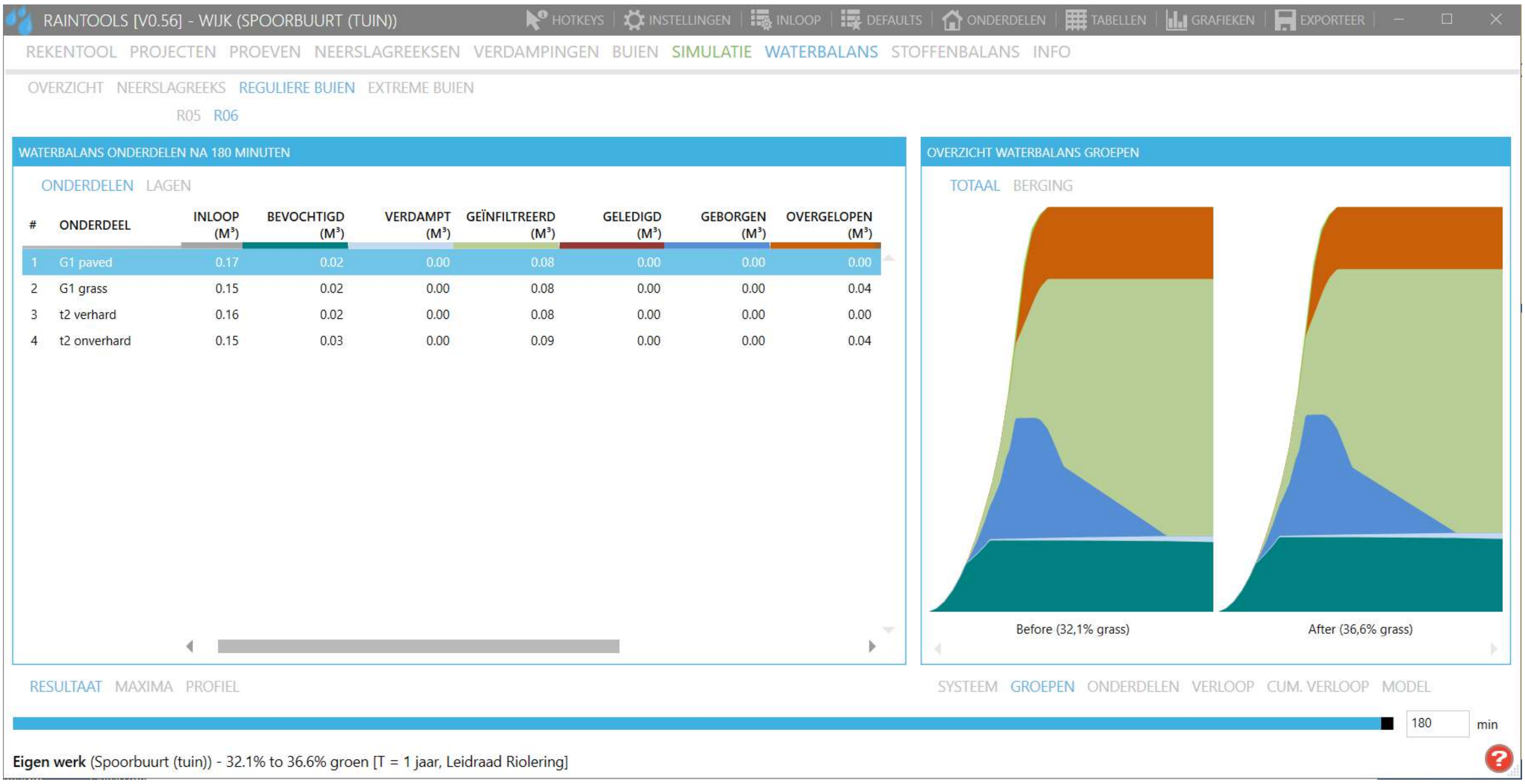
A13 *Water balance of hypothetical gardens (consisting of 0-100% grass) in time (180 min) during precipitation event R09, showing the increase in infiltration & storage in the soil and the decrease in the runoff & storage on the surface when the greening of the gardens enhances.*



A14 *Water balance of hypothetical gardens (consisting of 0-100% grass) in time (180 min) during precipitation event R10, showing the increase in infiltration & storage in the soil and the decrease in the runoff & storage on the surface when the greening of the gardens enhances.*



***A15** Water balance of hypothetical gardens (consisting of 0-100% grass) in time (180 min) the custom precipitation event (drizzle), showing the increase in infiltration & storage in the soil and the decrease in the runoff & storage on the surface when the greening of the gardens enhances.*



***A16** Output window of the Wijktegel for a simulation of a garden in the Spoorbuurt district before and after the greening during R06. The graphs depict the different terms of the water balance table in respect to time (180min). The colours correspond to the terms in the table which also lists their volumes in m³ for each layer that is defined in the model.*

Ethics Appendix

The percentage of paved area is increasing in urban residential areas (Perry and Nawaz, 2008). This growth in impermeable surface areas reduces the infiltration of precipitation into the soil, leading to more runoff. Most of the sewage systems of cities were not built for this extra runoff. In combination with the predicted increase in frequency of heavy precipitation events in the future (Pachauri and Reisinger, 2007) this will result in an overload of the sewage systems. As a consequence, cities and their inhabitants will have to deal with increasingly more floods.

One of the things that can be done to counteract this, is replacing part of the paved areas in residential gardens by vegetation. Research showed that this will not only decrease the runoff and therefore the risks of floods, but it will also reduce the heat stress in a city (Zwaagstra, 2014). Moreover, it will result in more habitat for plants and animals.

This solution, however, causes the following question to arise: is it ethical to force inhabitants to replace part of their paved garden with vegetation?

A person's garden is most of the time their private property. For that reason it could be debated that policy makers have no say in what someone should do with their own garden.

An alternative could be to replace parts of the public area that are paved at the moment. This would mean that replacement actions would be undertaken in parks or parts of the sidewalk for example. This alternative prevents people from being forced to do something in their own gardens and shifts the troubles to the municipalities. However, since the inhabitants of a city benefit the most from the action themselves, one could argue that they should be the ones to undertake action.

Many moral actors are involved in this dilemma. The owners of the paved gardens are for example not the only ones that will be affected. Other inhabitants of urban areas will also be troubled by the floods and heat stress. Moreover, since there will be more heavy precipitation in the future, next generations will profit even more if actions are undertaken right now. Policy makers of cities should therefore carefully consider what they do with this situation. Will they help the present and next generation knowing that there is a chance of displeasing some current inhabitants?

Other important actors to consider are the plants and animals which were originally present in the areas that are now paved. Do they not deserve some of their habitat back?

According to biocentrism they do. Obliging people to have less paved area and more vegetation in their gardens is in favour of these organisms and is therefore deemed ethical.

Someone that favours the anthropocentric view would however say that nature is inferior to humans. These people say that nature has merely a functional value and should serve the needs of the humans in whatever way is useful for them. Less paved area would mean less parking space and the extra vegetation requires more maintenance. This could be inconvenient for some people, especially when considering that not everyone has time to maintain their garden. Forcing people to change their gardens is thus considered unfavourable for humans and for that reason morally wrong.

However, contrasting about this view is that in this particular scenario, humans would at the same time also benefit from the action. Floods and heat stress would decrease and inhabitants will thus have less problems in comparison when no actions are taken. Ergo, it is difficult to draw conclusions based solely on this belief.

The intension of replacing the garden tiles with vegetation is to offset floods, lower heat stress and increase biodiversity. These are all good intensions, hence the action is justified according to the deontological theory.

Even though a garden might be someone's personal property, it should be considered that the consequences of not taking any actions are spread amongst many. According to Kant, the mentioned action is ethical because most people do not want floods or heat stress themselves and should therefore help to prevent these things from happening to other inhabitants and future generations. A similar ethical principal is that one should not harm others. Indirectly one basically gives future generations more floods and heat stress by keeping their garden paved. The increase in frequency of heavy precipitation events will cause the effects of the paving trend to enhance in the future making these troubles even worse. Thus, also according to this theory the action is justified.

When looking at it from a consequentialism point of view, it is also ethical. The action results in less floods, a lower heat stress and an increase in biodiversity, which are all positive consequences for other inhabitants, future generations and the flora and fauna. At the same time, the negative effects such as less convenient parking and more maintenance are only minor for the garden owners. This means that the action maximizes utility and is therefore just.

An important aspect of this problem is that the consequences of the actions are very diffuse. This means that when someone does not partake they can still profit since for them the risks of floods and the heat stress is still reduced. The other way around also applies: one can fully replace his garden without receiving any benefit because other people did not cooperate. It could therefore be difficult to persuade people into partaking because they do not trust that others will too or because they want to benefit without taking any action themselves.

Another moral question arises when looking at the executive part of this dilemma, because who is going to pay for the replacement? Making a cost benefit analysis could help answer this question. An example could be to compare the costs of possible sewer maintenance (which occur when no actions are taken) to the costs of the replacement actions. Based on this it can be decided to either replace some paved areas or bear the consequences. Policy makers could then also decide whether or not it is justified that they pay for it since normally the money for sewage maintenance will also come from them. Comparing the costs and effort of the replacement actions with the personal costs and effort that floods and heat stress will cause the people can also be a good measure to help persuade them into cooperating.

To conclude, it is deemed ethical to force inhabitants to replace part of their paved garden with vegetation. Although it could be difficult to convince people because of the diffuse consequences, the action does have the right intensions and is beneficial for the inhabitants themselves, future generations and plants and animals. Moreover, the negative effects are only minor and a cost benefit analysis could help to persuade people.

References

Perry, T., & Nawaz, R. (2008). An investigation into the extent and impacts of hard surfacing of domestic gardens in an area of Leeds, United Kingdom. Landscape and Urban Planning, 86(1), 1-13.

Pachauri, R. K., & Reisinger, A. (2007). IPCC fourth assessment report. IPCC, Geneva, 2007.

Zwaagstra, C. (2014). The contribution of soil sealing in urban private gardens to runoff and urban heating. University of Groningen.