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Ecosystem services provision; dependence of water quality and quantity

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Summary

Assessing ecosystem services provision dependence of water
Besides aesthetic value and recreational use of public green and blue space, there is a growing awareness that there are more benefits that people receive from green infrastructure and that these functions should be taken into account in planning and design. Effectiveness of green infrastructure for services such as temperature regulation, air quality regulation and runoff mitigation partly depends on sufficient availability and/or quality of water.

The aim of this assessment is to explore water dependence of ecosystem services in urban green infrastructure and to assess potential bottlenecks for a district in Utrecht. A method is proposed for analysis of water availability and water demand for ecosystem services provision by urban green infrastructure. The method has been applied in a case study in the city of Utrecht. As a first step, the focus of the case study analysis is on water requirements for ecosystem services provision by green spaces only. The analysis is targeted at the ecosystem services temperature regulation (cooling), stormwater runoff mitigation, air quality regulation, noise reduction, recreation and general wellbeing and water quality regulation.
In future projects, the analysis could be expanded to surface water (blue spaces) issues and to other ecosystem services.

Besides the current situation (2015), demand and supply have been analysed under expected future changes (2030 and 2050) as a result of climate change and land use changes.

Critical conditions
Two relations between the potential of green spaces for the provision of selected ecosystem services and (geo)hydrological conditions seem to be most critical: 1) the impact of low groundwater table and soil moisture content on the potential contribution of vegetation to *temperature regulation (cooling) via evapotranspiration* and 2) the impact of very wet conditions, when ponding occurs, on *recreation* potential of green spaces. A specialist from Utrecht municipality who is responsible for maintenance of green spaces stated that wet conditions currently pose more problems to urban green spaces than dry conditions. High groundwater tables limit the role of green spaces in stormwater runoff mitigation due to the reduced capacity of the soil to drain and store water.

Other relations between water conditions and ecosystem services of green spaces are only relevant under very extreme and long lasting conditions; for example the cooling effect of shading by trees may be effected when trees lose their leaves.

1) Current and future impact of drought on the potential contribution of vegetation to temperature regulation (cooling) via evapotranspiration
Current drought stress to vegetation has been assessed in 3 ways:
- an interview with a specialist from municipality Utrecht who is responsible for maintenance of green spaces;
- by comparing groundwater level with literature values for maximum rooting depth of trees and grass;
- by calculating drought stress with the urban water balance model.

Cooling is needed in summer and vegetation can provide this when sufficient water is available for (evapo)transpiration. The results of all three assessments show that drought

stress occurs during summer and that this affects vegetation in Utrecht. Drought stress is identified in areas where impervious pavement is surrounding the vegetation and where the topsoil constitutes of a layer of filling sand which results in low water holding capacity and quick groundwater discharge. Due to the high fraction of paved surface in the Jaarbeurs/Station district, a large part of the precipitation (49%) is drained by the sewer system either towards the surface water or waste water treatment plant. Only 27% of the rainfall infiltrates into the soil of which 42% is taken up by vegetation and transpires and 58 % percolates to the groundwater. Due to drought stress, actual transpiration of vegetation is on average 52% of the potential transpiration during the summer period (May-August). This reduces the cooling capacity of vegetation.

Based on the land use change and climate change scenarios, limitations as a result of geohydrological conditions to the service *cooling by evapotranspiration* provided by vegetation are not expected to worsen. At present groundwater levels range between approximately 0.2 m NAP and 0.4 m NAP (2.35 m and 2.15 m below surface level). The results of the simulation of climate change indicate that future changes in groundwater levels as a result of the local system are limited (less than 2 cm). Land use scenarios targeted at increasing the number of disconnected roofs, and increasing the percentage of water and permeable pavement indicate that these interventions will result in higher groundwater levels of up to approximately 0.1 m in summer. This may increase available soil moisture in summer times and lead to higher evapotranspiration rates. Increase of green spaces does not influence groundwater tables. By adding more green elements to the area transpiration, and thereby evaporative cooling, increases. This could cause an area average cooling effect of 0.23 ^{o}C.

2) Current and future impact of very wet conditions, when ponding occurs, on *recreation* potential of green spaces

Ponding may reduce the *recreational value of green spaces*. Groundwater data for the study area do not suggest problems with wet conditions but the maintenance team of the municipality identifies ponding problems at different locations in the city. However, ponding is in most cases the result of depressions and compaction of the topsoil rather than high groundwater tables. The results of the simulation of climate change indicate that future changes in groundwater levels are limited (less than 2 cm). The predicted increase in groundwater levels as a result of land use change will not lead to ponding of water on the surface as groundwater levels are still relatively deep. Deterioration of the recreational potential of green spaces is therefore not expected as a result of climate change or the assessed land use changes.

Recommended measures

In order to optimize the provision of *cooling by evapotranspiration* the following recommendations are provided:

- In areas with a high soil sealing grade, such as the Utrecht Jaarbeurs/station district, adding more vegetation will increase the potential evapotranspiration and as a result, will reduce the temperature in summer. See Gehrels et al., 2016 for more general information on the effectiveness of green spaces for cooling and design principles for effective (multifunctional) green spaces.
- In order to reach the potential cooling, drought stress should be reduced by increasing infiltration.
- At this moment, the municipality irrigates trees with the aim to prevent destruction of capital. For the benefit of temperature regulation, irrigation of other types of

vegetation could be considered. However, this study did not involve an assessment of the effectiveness and cost-efficiency of irrigation nor of the water demand.

- Reducing the amount of impermeable pavement, disconnecting roofs and increase of the amount of surface water (if connected to the groundwater system) are the most effective land use changes in order to improve water availability to vegetation.
- If it is not possible to increase infiltration by reducing the amount of soil sealing, infiltration measures in which runoff water is collected and infiltrated into the soil can be applied.

In order to optimize the *recreation* services of green spaces the following recommendations are provided:

- Measures that result in lower surface runoff will reduce ponding.
- Measures to prevent or reduce compaction will increase the infiltration capacity of the soil. Since the groundwater level is relatively deep in Utrecht, the use of the drainage and storage capacity of the soil can be optimized in this way.

1 Ecosystem services in urban areas

1.1 Background

There is increasing interest in opportunities for optimization of public green infrastructure[1] for ecosystem services[2] delivery. Besides aesthetic value and recreational use of public green and blue space, there is a growing awareness that there are more benefits that people receive from green infrastructure and that these functions should be taken into account, strengthened and optimized in planning and design. Effectiveness of green infrastructure for services such as temperature regulation, air quality regulation and runoff mitigation partly depends on the availability and/or quality of water. Examples of the practical questions in this context from urban water managers are 'when is a tree affected by high or low groundwater levels?' and 'what is the effect of water availability in the soil on evaporation and air cooling?'. The relation between water and the effectiveness of urban green infrastructure is being explored in this report.

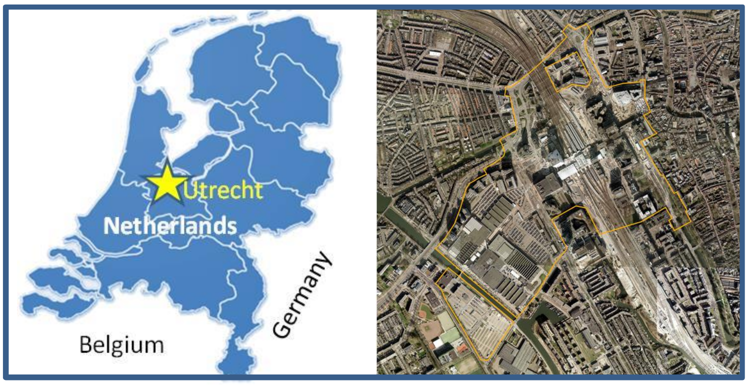
1.2 Aim

The aim of this activity is to explore water dependence of ecosystem services in urban green infrastructure and to assess potential bottlenecks for a district in Utrecht. In favour of this aim, a method will be proposed for analysis of water availability and water demand for ecosystem services provision by urban green infrastructure. The method will be applied in a case study in the city of Utrecht.

1.3 Study area

The study area 'Utrecht Centre-West' is located in the city centre of Utrecht, the fourth largest city in the Netherlands with 330,000 inhabitants, and covers the area around the central train station and the Jaarbeurs fair. The area is characterized by a high percentage of buildings and pavement (see Figure 1.1). Most of the office buildings, housing and exhibition halls in this district were built in the 1960s. Since shopping areas are not up to date, and traffic and water infrastructure are outdated the municipality of Utrecht formulated an ambitious redevelopment plan together with the business community and local citizens (Van de Ven et al., 2016).

Figure 1.1 The study area 'Utrecht Centre-West' is located in the city centre of Utrecht. The orange line on the right hand photo indicates the boundaries of the area.



[1] Green infrastructure: the spatial structure of natural and semi-natural areas but also other environmental features which enable citizens to benefit from its multiple services (COM, 2013).

[2] Ecosystem services: goods and services that are provided by ecosystems and that are beneficial to humans.

1.4 Approach

Potential ecosystem services of green infrastructure are listed together with their dependence of water quality and quality. The list is included in an assessment framework for further assessment of this dependence.

As a first step, the focus of the case study analysis will be on identifying water requirements general for ecosystem services provision by green spaces. In future projects, the analysis could be expanded to surface water issues.

In the second step, a literature review is conducted to specify the water conditions limiting potential provision of selected ecosystem services of green spaces.
Third, a water balance model is used to identify potential bottlenecks in ecosystem services delivery in the study area due to water quantity issues. Besides the current situation (2015), demand and supply will be analysed under expected future changes (2030 and 2050) as a result of climate change and land use changes.

2 Method for assessment of demand and supply of water for ecosystem services at the district level

For assessment of the demand and supply of water for ecosystem services delivery by the urban green spaces, a structured method is proposed.

2.1 Stepwise assessment framework

Step 1) Inventory of relevant ecosystem services which are currently being used and/or that are demanded in the future.
The list of ecosystem services as provided in table 2.1 can be used as long list from which services that are relevant for the research area can be selected. The list is not limited to ecosystem services delivered by green spaces but also includes services of surface water and groundwater systems. It is recommended to perform a selection together with stakeholders and specialists from different relevant disciplines.

Step 2) Assessment of the dependence on water quality and quantity for ecosystem service delivery.
Table 2.1 can be used to identify potentially relevant relations between ecosystem services delivery and water quality and quantity. This step is conducted for the ecosystem services that have been selected in step 1.
Identified potential limiting conditions can be further elaborated with general knowledge from literature. A start has been made in this project by assessing the potentially limiting geohydrological conditions for ecosystem services provision by vegetation (see section 2.3).

Step 3) Assessing water availability
A water balance model is being used for a first estimation of potential bottlenecks in ecosystem services delivery due to groundwater quantity issues. The model will be used to assess water availability in various scenarios that differ in climate conditions and land use. The water balance model is briefly described in Appendix 1.

The water balance model can be used to determine groundwater levels and evapotranspiration fluxes. Before the model can be used, research questions need to be formulated based on the results of step 2. The research questions refer to potential problems in ecosystem services delivery based on conditions that are too wet or too dry.

For assessment of water quality issues, existing standards (such as drinking water standards, standards for swimming water) can be used or new criteria can be developed based on literature and/or stakeholder’s demands. A water quality assessment framework with key factors for ecosystem services provision is currently being developed.

2.2 Ecosystem services and water dependence

Table 2.1 provides an overview of the dependence on water quality and quantity for ecosystem services delivery.

Table 2.1: Dependence on water quality and quantity for ecosystem services delivery. Explained for ecosystem services related to green spaces, surface water, and groundwater use.

Effectiveness limited by Ecosystem services	Quantity	Quality	Timing	Remarks
Green spaces (groundwater and soil moisture attributes)				
Temperature regulation (cooling) through: - shadow - evapotranspiration - heat exchange	- no - yes - yes	- no - no - no	Water needed for evapotranspiration in summer, in particular during hot & dry spells	Shadow function only affected when tree loses leaves due to severe drought or raising groundwater*. Drought limits evapotranspiration; especially grass susceptible to drought.
Storm water runoff mitigation through: - interception - infiltration - surface storage in green spaces with low surface level	-no - yes;	- no - no - yes, indirect	Slowdown of discharge desirable during heavy rain (intensity and duration) to prevent sewer overflow and flooding	Interception only affected when tree loses leaves due to severe drought or raising groundwater*. In dry situation (summer): hydrophobic soil hampers infiltration Under very wet conditions (high groundwater table) : limited or no storage capacity Quality of the storm water could make direct infiltration undesirable although treatment by soil filtration is generally sufficient
Air quality regulation through - influence on air circulation - filtering air pollutants	- no - yes	- no - no	Services by deciduous vegetation altered by season (presence of leaves)	Influence on air circulation (either positive or negative) and particulate matter capture altered when tree loses leaves due to severe drought or raising groundwater*. Drought or very wet conditions may reduce the vegetation's effectiveness for absorption of gasses through the stomata of vegetation (they close).
Noise reduction through - noise reduction - reduced perception when noise source visually camouflaged	- no - no	- no - no	Services by deciduous vegetation only delivered during spring and summer	Noise reduction only affected when tree loses leaves due to severe drought or raising groundwater*.

General wellbeing and recovery through: - green environment	- no	- no	Services by deciduous vegetation only delivered during spring and summer	Uncertain: Only directly affected when tree loses leaves due to severe drought? Indirectly, this service may be limited by ponding (reduced storm water runoff mitigation)
Recreation in green environment	- no	- yes/no		Uncertain: Only directly affected when tree loses leaves due to severe drought? Indirectly, this service may be limited by ponding (reduced storm water runoff mitigation)
Water quality regulation via: - uptake of pollutants from soil (eg heavy metals) - capture of pollutants from air and surface runoff	- yes	- yes/no	Services by deciduous vegetation altered by season (presence of leaves)	Toxicity may harm the vegetation
Food production	- yes	- yes		Food security is an issue (soil/groundwater quality).
Biomass production (eg wood)	- yes	- yes		Groundwater quality may limit use options.
Surface water				
Recreation: - swimming - boating - fishing - walking, biking etc - skating	 - yes - yes - yes - no - yes	 - yes - yes - yes - no - no	 - summer - spring-summer - all year - all year - winter	 Minimum depth required Certain quality required (swimming water standards, ecological parameters for fishing, transparency and smell) Skating requires constant water level In times of drought, recreation is latest (4th)priority in water distribution policy.
Water purification, pollution retention	- yes	- yes	- service provision influenced by season	Natural purification processes depend on oxic/anoxic conditions, light, flow velocity, retention time (size of water body), bed sediment conditions, macrophytes growth, etc.
Water for industrial extraction	- yes	- yes	- service provision may be influenced by season (freezing)	Resource limited by quantity and quality of the water, freezing In times of drought, industrial water is 3rd priority in water distribution policy.
Water for drinking water extraction	- yes	- yes		The closer the water quality to drinking water standards, the better. In times of drought, drinking water is 2nd priority in water distribution policy.
Space (e.g for shipping, housing)	- yes	- yes (for housing)		Depth, size and quality of water can limit functionality

Temperature buffering (for cooling water discharge)	- yes	- yes	Allowed discharge limited during dry and warm periods	Max. Temp is limited to increase surface water 3 ºC, max 28 °C.
Thermal energy (for harvesting)	- yes	- yes		Harvesting heat and cold is possible if size of surface water body is sufficient. Circulation of surface water should be sufficient; In times of drought, energy provision is 2nd priority in water distribution policy.
Irrigation water	- yes	- yes		
Water storage and discharge water surplus	- yes	- no		Quality of discharge water make storage undesirable
Groundwater (phreatic and first aquifer)				
Drinking water	- yes	- yes	Currently from deep groundwater, potentially 1st aquifer in future	The closer the water quality to drinking water standards, the better. In times of drought, drinking water is 2nd priority in water distribution policy.
Irrigation water	- yes	- yes		Quality requirements: mainly chloride and iron and bacteria important. In times of drought, energy provision is 3rd or 4th (depending on crop value) priority in water distribution policy.
Water for industrial extraction	- yes	- yes		Resource limited by quantity and quality of the water. In times of drought, industrial water is 3rd priority in water distribution policy.
Temperature buffering, for Aquifer Thermal Energy Storage	- no	- yes		Water quantity is more important than quality. Changes in redox conditions (e.g. as result of groundwater remediation or extractions) can result in clogging of the well.
Water quality regulation	- no	- yes		Filtration and hydro(geo, bio)chemical reactions improve groundwater quality.
Prevention of land subsidence and peat oxidation	- yes	- yes		High groundwater levels reduce subsidence; Anoxic conditions to prevent peat oxidation
Water storage	- yes	- no		Capacity depends on groundwater table/volume unsaturated zone and pore size.

Note: deciduous vegetation loses leaves in winter but this effect is not described in this table since it is not related to the quality of availability of water.

2.3 Potential limiting conditions for ecosystem services provision

In green spaces, groundwater is influencing ecosystem services delivery. The literature review has been targeted at relations between groundwater conditions and ecosystem services of green spaces in temperate climate zones. For this pilot study, the analysis is limited to an assessment of the quantitative groundwater conditions, assuming that groundwater quality is not significantly limiting the potential of vegetation to deliver the selected ecosystem services mentioned in section 3.1.

Table 2.1 has been used to determine which of the selected services may be limited due to water availability issues in terms of soil moisture content and groundwater level.

Low soil moisture content may limit the effectiveness of:

- soil in provision of runoff mitigation (infiltration). Effect of drought: infiltration capacity is reduced (strongly) in dry soils as the unsaturated hydraulic conductivity decreases with lower soil moisture contents. Next to that water repellency may occur in sandy soils. Indirectly this may also limit the potential recreational use of green spaces due to ponding stormwater.
- vegetation in the provision of cooling (evapotranspiration). Effect of drought: closing stomata, dry leaves, withering.
- vegetation in absorption of gasses through the stomata of vegetation.
- vegetation on general wellbeing related to the visual perception of green spaces and recreation (yellow leaves).

Soil data were hardly available for the project area. Therefore only general remarks can be made on the effect of drought on limiting infiltration rates. If we assume that vegetation is planted in a sandy clay loam with sufficient organic matter (as is often the case in the Netherlands) infiltration rates will only slightly be reduced due to low unsaturated infiltration capacities. In case of grass under heavy recreational use there is a risk of low infiltration rates due to topsoil compaction and water repellency.

Green spaces can enhance the role of soil in water quality regulation. If stormwater runoff from pavement and buildings can infiltrate into the soil, physical, chemical and biological processes can remove and often degrade pollutants. Severe drought may influence infiltration patterns and surface runoff. It is not possible to generate highly simplified relations between soil moisture content and infiltration; this issue will therefore be excluded from the analysis in the Utrecht case study.

In order to determine at which soil moisture content levels water is available to plants, one should consider the soil moisture retention (or pF-) curve of the specific soil. This curve shows how much suction pressure applies at different soil moisture levels. Vegetation can only take up water from the soil pores if the suction pressure is below 4.2 (wilting point). If pF is lower than 2 water in the unsaturated zone will easily leak down to the saturated zone. The maximum duration of dry conditions that vegetation can bear varies between species (Baughman, 2010). Some will die after a few days of lack of available soil moisture, others (trees) can survive without water for longer periods (weeks to months). During the growing season, vegetation is more vulnerable to drought stress.

The impact of drought stress on absorption of gaseous air pollutants will, in the Netherlands, be limited to short periods. Besides, the effectiveness of vegetation for absorption of pollutants is relatively low (order of magnitude of less than 1 to several percent of the pollutant concentration in the air)[3]. We therefore assume that the impact of low soil moisture content on air quality regulation is not a key issue to further assess.

The impact of drought symptoms (wilting, yellow leaves) on the aesthetic value of green spaces and the effect on wellbeing are not known. A more extended literature review may result in better insight in this matter if there has been research on this issue at all.

The less water in the unsaturated zone and the higher the pF, the less actual evapotranspiration. Since no soil samples are available in this project, the calculated soil moisture content cannot be translated to a pF-curve and evapotranspiration by vegetation. As an alternative, groundwater levels will be used as an indicator for potentially too low soil moisture contents in the rooting zone which may affect the role of vegetation for cooling. The impact of dry conditions on the cooling capacity of green spaces is relevant because dry and hot conditions will often coincide.

Low groundwater table may limit the effectiveness of:
- vegetation in the provision of cooling (evapotranspiration).

Since no pF-curves are available for the study area (see previous paragraph), groundwater level is used as a first indicator for potential drought problems. Following a global review of rooting depth by Canadell et al. (1996), the maximum rooting depth is
- 1,8 m to 4,4 m for temperate deciduous trees
- 2,0 to 7,5 m for temperate coniferous trees;
- 1,2 to 6,3 m for temperate grassland vegetation (not only grass species).

For the review, Canadell et al. used references which had species- or community-level information on root depth below 1.0 m. The data for temperate deciduous and coniferous trees are presented in figure 2.1.

Fast lowering of groundwater level may limit the effectiveness (when plant cannot adapt fast enough by growing new roots) of
- vegetation in the provision of cooling (evapotranspiration). Effect of drought: closing stomata, dry leaves.
- vegetation in absorption of gasses through the stomata of vegetation.

It is not possible to determine what pace of lowering is too fast to create drought related problems in vegetation as this process is highly complex based on species, local soil type and antecedent conditions.

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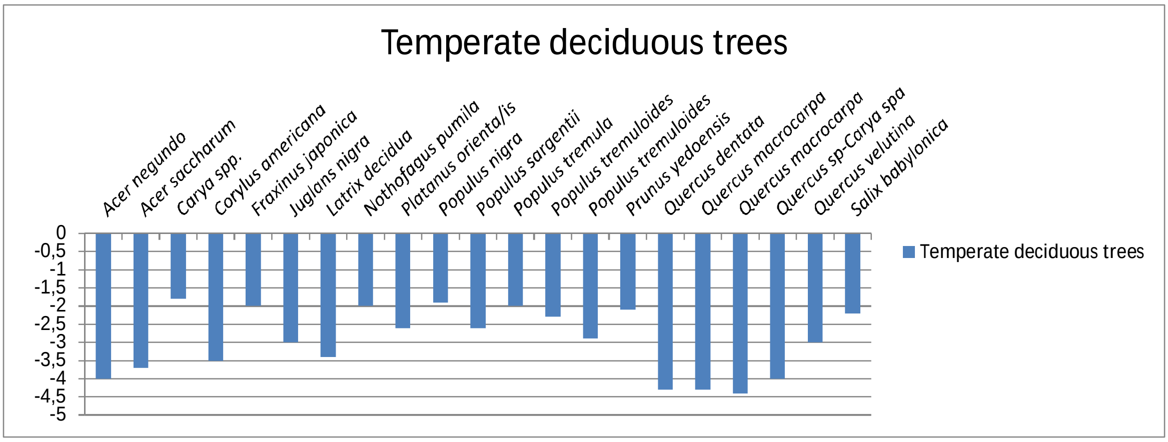
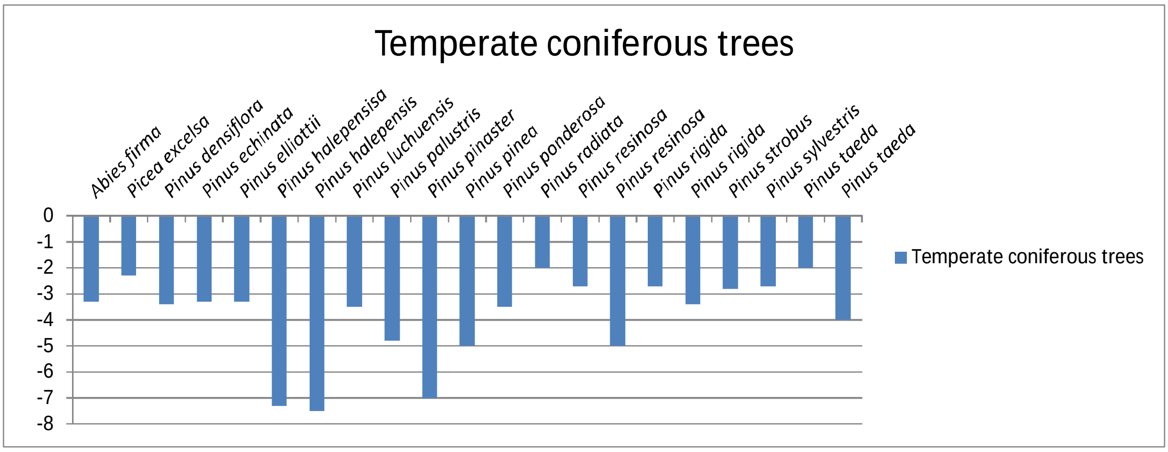
[3] *See the report 'Healthy urban living; Designing green and blue infrastructure to foster healthy urban living' (in prep.) for the results of a literature review on the effectiveness of green spaces on air quality.*

Figure 2.1 Maximum rooting depth of temperate deciduous trees and coniferous trees (graph based on data from Canadell et al. (1996).





Wet conditions (high soil moisture content in topsoil; high groundwater table; ponding) *may limit the effectiveness of*

- soil in provision of runoff mitigation (infiltration). In case of a high groundwater table, drainage and storage capacity is limited.
- vegetation in the provision of cooling (evapotranspiration). Effect of drought: closing stomata (due to toxic effect).
- vegetation in absorption of gasses through the stomata of vegetation.

In case of long lasting wet conditions (soil moisture higher than field capacity; flooding), vegetation will not be able to provide the services mentioned in section 3.1. For example, most trees can bear four months or longer periods of flooding outside the growing season. During growing season however, vegetation is more vulnerable for damage due to wet conditions. Most vulnerable species can bear one to two weeks of continuous flooding before they are seriously damaged; least vulnerable species three to five weeks (Baughman, 2010). Ponding may also limit the recreational use of green spaces. When grass lanes are flooded, they are not useful for activities such as picnicking or sports.

Impact of extreme and long lasting drought or wet conditions on vegetation
Several services of vegetation (such as providing shade or noise reduction) will only be hampered severely if leaves are lost due to severe and long-lasting drought or severe and long-lasting wet conditions during the growing season, especially in case of fast changes or long lasting unfavorable conditions. Since it is not expected that these extreme situations will occur regularly and/or at large scale in Utrecht, the impact on these services is neglected in this analysis.

3 Analysis of water availability for green infrastructure in the Utrecht Centre West district in Utrecht

3.1 Relevant ecosystem services

For this pilot study, the analysis is limited to key ecosystem services of green elements. A first selection has been made by the project team of societal challenges that are relevant for Utrecht. These have been identified during a workshop for the project Adaptive Circular Cities with participants from different fields of expertise from municipality Utrecht.

First selection of key ecosystem services:

- Temperature regulation (cooling)
- Stormwater runoff mitigation
- Air quality regulation
- Noise reduction
- Recreation and general wellbeing
- Water quality regulation

3.2 Dependence of green elements on water; potential limiting conditions

Considering the information in chapter 2.3 it seems that one relation between the potential of green spaces for ecosystem services delivery and geohydrological conditions is most critical: the impact of low groundwater table on the potential contribution of vegetation on temperature regulation via evapotranspiration and the impact of very wet conditions on recreation potential of green spaces.

Ponding is limiting the potential of green spaces to accommodate for recreational activities but in Utrecht this is mainly due to compaction of the topsoil and not the result of high groundwater tables. However, high groundwater tables may result in ponding, therefore this mechanism will be discussed in the scenario studies for impacts on groundwater level.

High groundwater tables limit the role of green spaces in stormwater runoff mitigation; not because of a significant impact on the interception capacity vegetation, but due to the reduced capacity of the soil to store water.

Other relations between groundwater conditions and ecosystem services are only relevant under very extreme and long lasting conditions (e.g. when vegetation loses leafs).

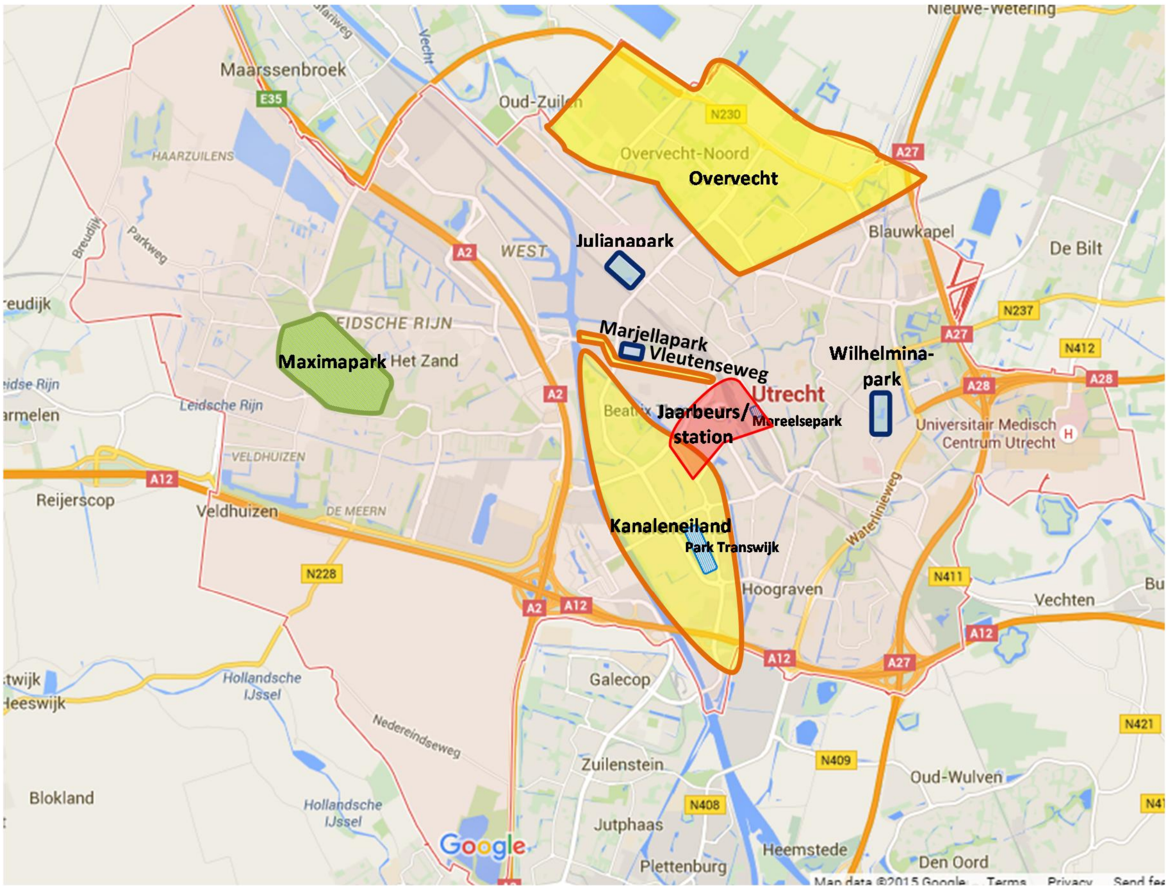
3.3 Assessing water availability

3.3.1 Currently perceived impact of dry and wet conditions on green infrastructure in Utrecht

A specialist from municipality Utrecht responsible for maintenance of green spaces has been interviewed about current damage to vegetation as a result of dry or wet conditions. According to the interviewee, wet conditions currently pose more problems to urban green spaces than dry conditions.

Wet conditions are defined as situations in which water is ponding on the surface and/or groundwater table is close to the surface. This occurs for example in Marjella Park, Wilhelminapark and Juliana Park (see Figure 3.1 for locations). Wet conditions affect trees by causing root decay, which sometimes leads to falling trees. Ponding is also perceived as a problem because it decreases the opportunities for recreational use of green spaces. The main causes for ponding are reduced infiltration capacity due to compaction of the soil by intensive use of the area, the presence of an impervious top layer and topography (depressions). In some parks, special measures consisting of artificial turf (grass) and special substrates have been taken to mitigate the compaction effect of intensive recreational use. This is the case e.g. in Park Transwijk and in Moreelse Park. In some parks, for example Maxima Park, both drought problems and ponding occur. Construction of small ditches has proven to be an effective measure to solve ponding.

Figure 3.1 Locations or districts where drought stress results in observable impact on vegetation (yellow), where ponding is observed (blue), where measure to prevent compaction are taken (white/blue), where both dry and wet conditions occur. The red area indicates the study area with the Jaarbeurs fair and train station.



Symptoms of drought stress are yellow vegetation (trees, grass and perennials) and sometimes even loss of leaves. Drought stress is identified in areas where impervious pavement is surrounding the vegetation and where the topsoil consists of a layer of filling sand which results in low water holding capacity and quick groundwater recharge. Filling sand is applied before building activities started with the aim to improve carrying capacity of the soil (stability) and for its drainage capacity. Trees (outside parks) in these areas are usually planted in a small pit in which a cubic meter of mould (garden soil) has been applied. This practice was common in areas that have been developed in the ‘50s and ‘60s such as the districts known as Overvecht and Kanaleneiland. In neighborhoods that have been built before, less filling sand has been used, in younger areas filling sand has been applied more targeted (e.g. only under buildings and infrastructure). The latter situation leads to ponding since the areas where no filling sand has been applied (mainly parks and other green spaces) are now lower lying areas where water accumulates. Besides drought due to unfavorable soil conditions and soil sealing, groundwater extraction for building activities (to drain the building excavation site) results in drought stress during the growth season if the lowering of groundwater tables lasts for months.

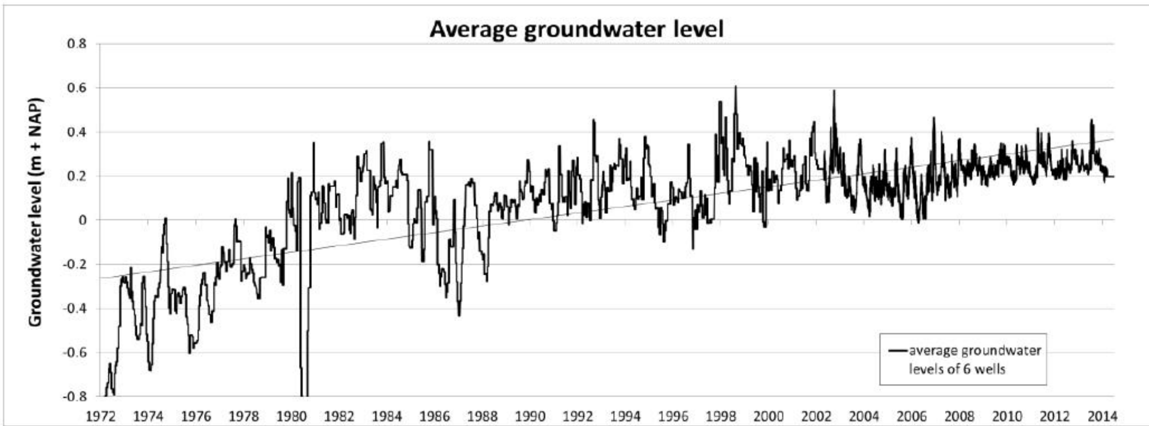
Irrigation of public green spaces maintained by the municipality takes places in some areas where drought affects trees such as is the case with trees along the road Vleutenseweg. Irrigation is limited to trees because of the high costs of irrigation; trees are watered because loss of trees is perceived as destruction of capital. The functionality of grass lawns for recreation is not perceived as being decreased due to drought. When asked about the reduced cooling capacity of grass (via evapotranspiration) during drought, the interviewee prefers to ensure that other types of vegetation (shrubs and trees) keep functioning during dry periods.

3.3.2 Current groundwater conditions in relation to potentially limiting conditions for ecosystem service provision

3.3.2.1 Comparing root depth and groundwater level

Groundwater levels in the area around Jaarbeursplein/Station are shown in Figure 3.2. The location of six monitoring wells from which the groundwater levels have been used to calculate the average groundwater level in the area are shown in Appendix 2. During the measurement period the groundwater level has been rising. At present groundwater levels range between approximately 0.2 m NAP and 0.4 m NAP (2.35 m and 2.15 m below surface level; surface level is +2.55 m NAP).

Figure 3.2 Average groundwater level based on six monitoring wells (see Appendix 2) around Jaarbeurs/Utrecht Central Station. Surface level is +2.55 m NAP. From Molenaar (2015).



The maximum rooting depths of plant species as presented in paragraph 2.2.2 can be used to get a first impression of potential impact of drought on vegetation. According to Candell's list, maximum rooting depths of deciduous trees range between 1,8 and 4,4 m. The average groundwater table in the study area of 2.35 m to 2.15 seems to be high enough for many tree species but not all. It is uncertain to what extend the species in the list of Canadell are representative for the tree species that are common in Utrecht. De Jong (2015) listed the top 10 of most abundant species of public trees and other vegetation types in two neighborhoods, Tuindorp and Overvecht, of Utrecht (outside the study area of this project). The species from that list are not included in the review of Canadell. Hands on experiences from municipalities green keepers' in combination with soil profile and groundwater data can provide a more reliable prediction of potential drought related problems with future trees in the study area. Green keepers experience (see section 3.3.1) shows that in some areas in Utrecht, especially in areas with high soil sealing grade and application of filling sand, trees do suffer from drought during dry periods.

Most commonly used grass species for public green Utrecht[4] are *Lolium perenne* and *Poa pratensis*; these species are not included in the review by Canadell but in grey literature, maximum rooting depths of 94 to 100 cm are found[5]. These values are relatively close to the smallest root depths in temperate grasslands reported by Canadell. One of species that is also applied is *Festuca rubra*, which has a more shallow estimated rooting depth of 30-50 cm. The difference between the maximum rooting depth and the groundwater level in the study area is more than 1 m for grass. The observation of the municipality is that during most time of the year, grass in Utrecht is green, and no irrigation is applied. During dry periods however, grass leaves turn yellow and stop evaporating due to drought stress.

Groundwater data for the study area do not suggest problems with wet conditions in relation to vegetation health and runoff mitigation by. However, the maintenance team of the municipality identifies ponding problems at different locations in the city. However, ponding is the result of depressions and compaction rather than high groundwater tables.

3.3.2.2 Drought stress based on the water balance model

Figure 3.3 shows the main water fluxes in the study area. The annual precipitation is 887mm per year. Of this precipitation 13% is intercepted by vegetation and the land surface from which it evaporates. Due to the high fraction of paved surface, a large part of the precipitation (49%) is drained by the sewer system either towards the surface water or waste water treatment plant. Only 27% of the rainfall infiltrates into the soil of which 42% is taken up by vegetation and transpires and 58 % percolates to the groundwater. This means that only 9% of total precipitation is transpired.

Figure 3.4 shows water stress calculated by the Urban Water Balance Model. Water stress is defined as the normalized difference in soil moisture content at which potential transpiration occurs and the actual soil moisture content. Mean monthly values show that water stress occurs in all years and that stress in a dry year is much higher than in an average year. During drought stress, vegetation can transpire less than potentially possible under optimal soil moisture conditions. This is also reflected in Figure 3.5, where the actual and potential transpiration are shown. The potential transpiration during the summer period (May-August) ranges between 80 mm/month and 95 mm/month while the actual between 35 mm/month and 51 mm/month. The relatively low actual transpiration is due to water shortage.

[4] *Information from personal communication with Wim de Wolf, municipality Utrecht (15 October 2015)*

[5] *Luske et al., 2012. Beworteling van grasland en droogtetolerantie Maatregelen voor een diepere beworteling.; also wildeplanten.nl and verspreidingsatlas.nl.*

Figure 3.3 Schematization of the water system at Utrecht Station area with main water fluxes for the reference period 1981-2010. The figure shows the yearly sums of water fluxes.

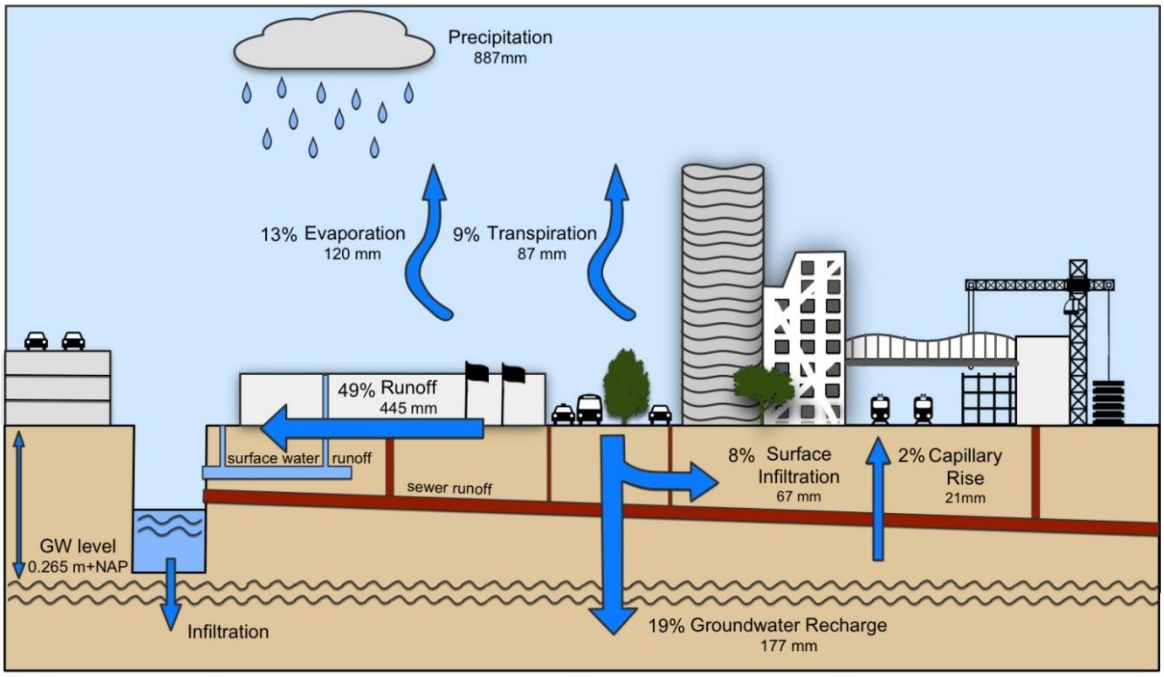


Figure 3.4 Water stress calculated by the Urban Water Balance Model. Water stress is defined as the normalized difference in soil moisture content at which potential transpiration occurs and the actual soil moisture content. Mean monthly values show that water stress occurs in all years and that stress in a dry year is much higher than in an average year.

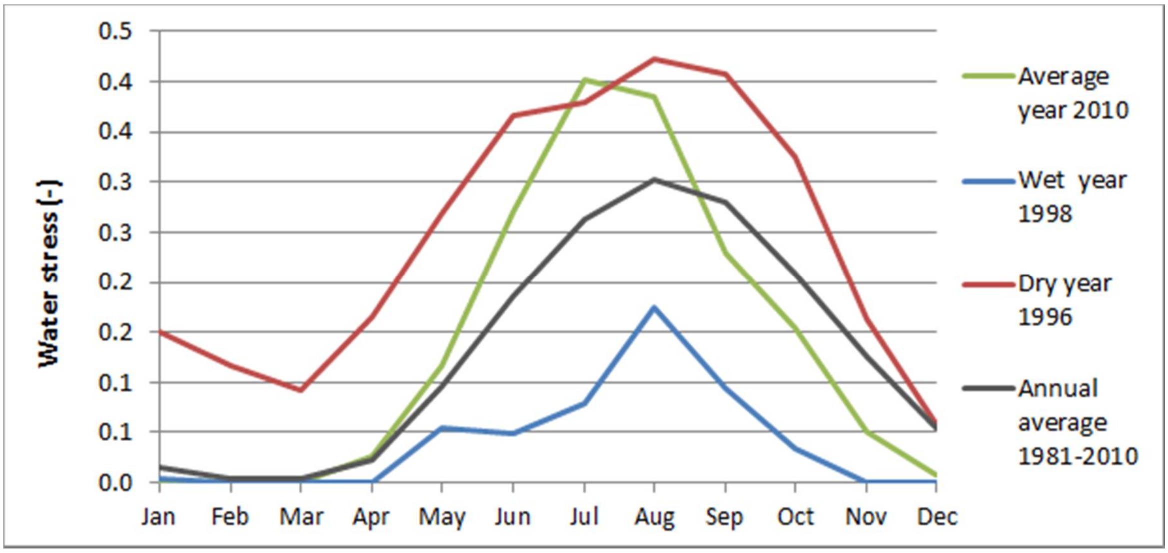
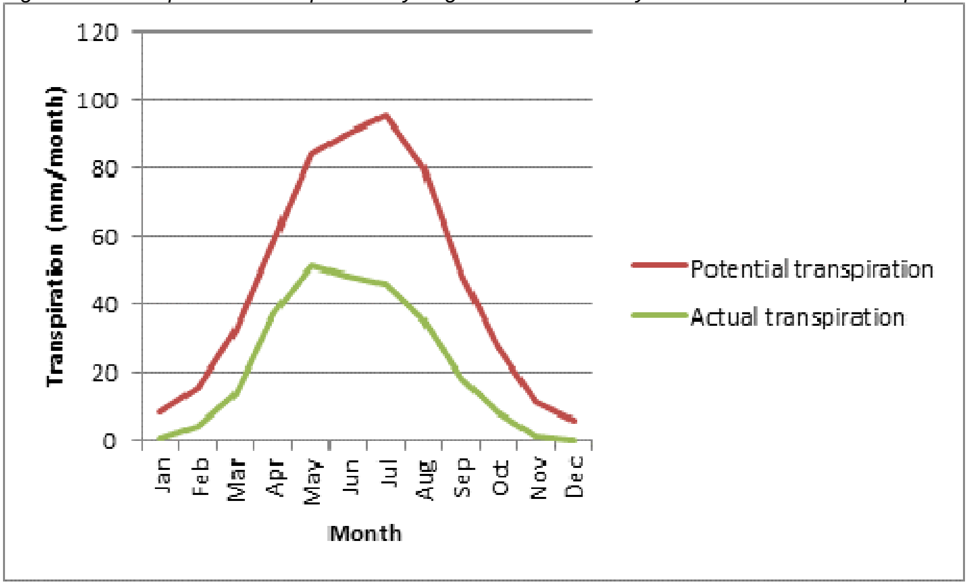


Figure 3.5 The potential transpiration by vegetation in the study area and the actual transpiration.



3.3.3 Future scenarios for changes in groundwater levels

In order to explore if groundwater conditions may become more or less favorable for vegetation in the future, climate change and land use change scenarios have been applied to the water balance model for the study area.

3.3.3.1 *Climate change*

The Royal Netherlands Meteorological Institute (KNMI) has developed the 'KNMI-14 climate projection' to generate precipitation values for the four climate change scenarios of KNMI (Figure 3.6). Both G projections are based on an air temperature increase in 2050 of 1^{o}C and the H projections assume an air temperature increase in 2050 of 2^{o}C. The projection shows that extreme rainfall events of 30 mm or more and 40 mm will occur 1.3 to 1.6 times more often in 2030 and 1.7 to 2.4 more often in 2050. In 2030, precipitation on yearly basis will be 915.8 to 938.4 mm, depending on the scenario, instead of 887 mm for the reference period 1981-2010. Two scenarios, GH and WH, project a drier summer with less precipitation compared to the current climate. More details on received precipitation for each month, summer, winter and year are given in Molenaar 2015 and by KNMI.

3.3.3.2 Land cover change

Current land cover of the study area is summarized in table 3.1. For assessment of the effect of land use changes on groundwater level, changes as presented in table 3.2 have been assumed.

Figure 3.6 The four KNMI'14 scenarios; the scenarios differ in the extent to which the global temperature increases (G: moderate, W: warm) and the possible change of the air circulation pattern (L: low value, H: high value).

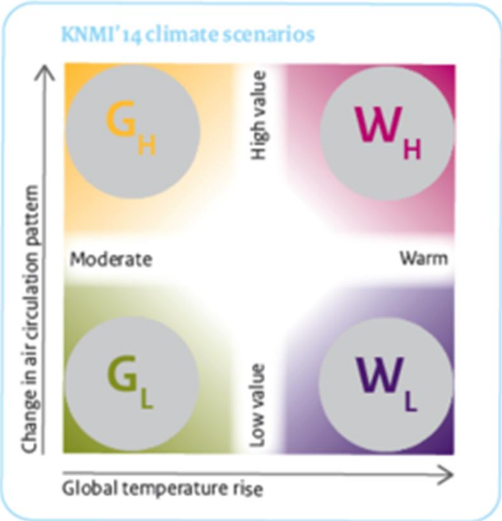


Table 3.1 Land cover (situation 2011; from Molenaar, 2015)

Land cover	**%**
Paved, impermeable	18
Paved, semi-permeable	23
Paved, permeable	1
Roof, sloping	0
Roof, flat (no green/blue roofs)	24
Unpaved*	33
Water	1
TOTAL	**100**

* In the water balance model, all unpaved space is considered to be green space because most of the unpaved space in the Netherlands is vegetated. In reality, unpaved land in the Jaarbeurs/Station district consists of railway tracks (7%) and green space (26%).

Table 3.2 Land use scenarios and the related interventions.

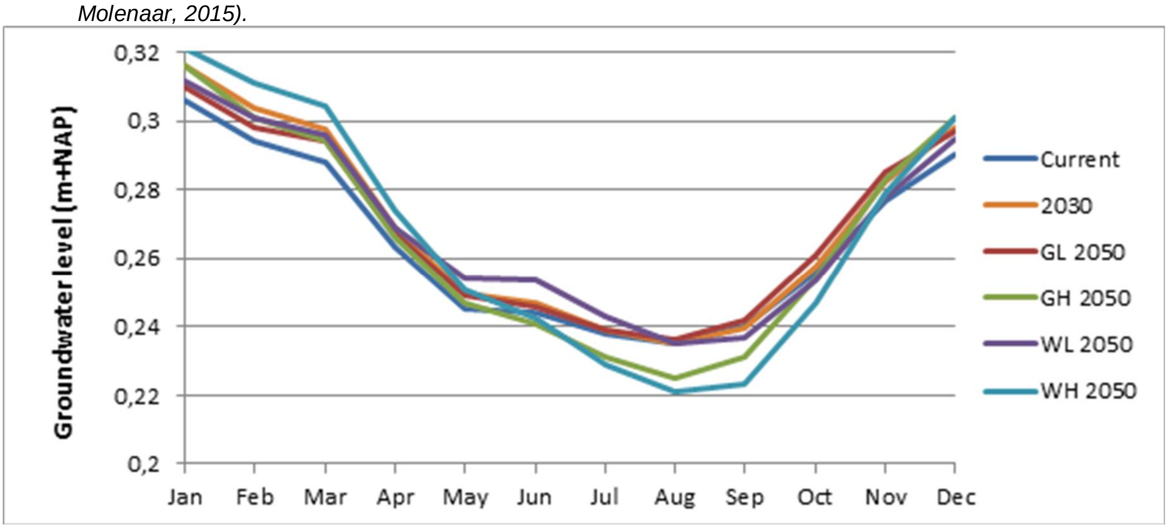
Scenario / Intervention	**Intervention**
Green roofs extensive	Extensive green roofs are implemented on all flat roofs in the area
Green roof intensive	Intensive green roofs are implemented on all flat roofs in the area
Water retention	Blue roofs are implemented on all flat roofs in the area
All permeable pavement	All paved and semi-permeable paved area is replaced by highly permeable pavement
Semi-permeable pavement to permeable	Semi-permeable pavement is replaced by permeable pavement systems
More vegetation (from 33% to 40%	Paved area is reduced to create 21% more vegetation
Disconnection roofs	All flat roofs are disconnected
More paved surface	114% extra paved surface by reducing unpaved area
More surface water (x2)	100% more surface water by reducing paved area

3.3.4 Results of water balance model scenario runs

3.3.4.1 Projected changes in groundwater level due to climate change

All climate change scenarios result in an increase of the average yearly groundwater level (see figure 3.7). In summer, the G_H and W_H scenarios show lower groundwater levels which results from lower precipitation rates and increased evapotranspiration rates. In winter, all scenarios show higher groundwater levels as a result of increased winter precipitation. The projected changes are relatively small, less than 2 cm, partly due to the large amount of paved surface and buildings and the fixed head of the deep groundwater in all scenarios.

Figure 3.7 Comparison of groundwater levels (m+ NAP) for the current climate and different KNMI-scenarios (from Molenaar, 2015).



3.3.4.2 Projected changes in groundwater level due to land use change and green/ blue roofs

Figure 3.8 shows that increasing surface water by adding canals, disconnecting roofs and increasing permeable pavement are expected to have the largest influence and result in an increase of the groundwater level over the year with a maximum increase of almost 15 cm. An increase of non-permeable paved surface results in a lower groundwater level over the year of approximately 3 cm.

Changes in evapotranspiration and infiltration as a result of increased vegetation cover from 33% to 40% by adding for instance a park does not impact groundwater significantly. Green roofs have no impact on groundwater level because water from these roofs is drained via the sewage system, like with blue roofs.

3.3.4.3 Overview of effects land use changes

Table 3.3 provides an overview of the impact of land use changes and application of green and blue roofs.

Figure 3.8 Overview of the effects of different land-use scenarios on groundwater level. The curves for the reference, green roof and water retention roof scenarios overlap.

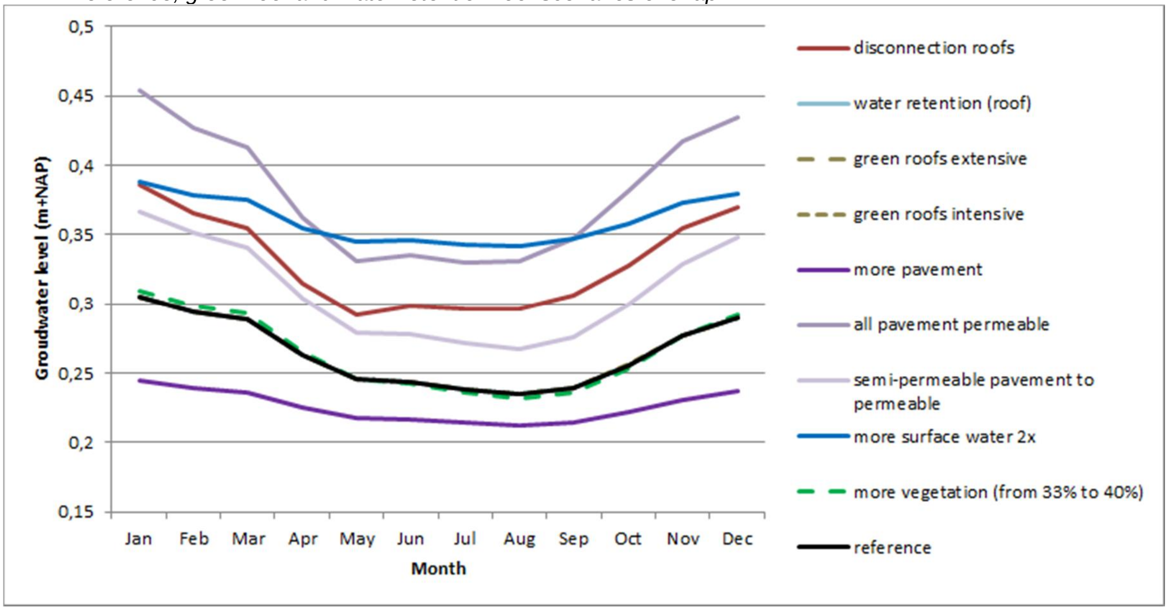


Table 3.3 Overview of predicted effects of land use changes and implementation of blue and green roofs in the study area.

Scenario	Intervention	Effects
Green roofs extensive	Extensive green roofs are implemented on all flat roofs in the area, while the roofs remain connected to sewer system	Extensive green roofs (<15cm) can store a limited amount of water in the growth medium and provide a limited reduction of total runoff from the area and peak discharge: 2% of rainfall is stored during extreme rainfall events and up to 16% for small rainfall intensities. As the roofs discharge towards the sewer system these roofs have no effect on the groundwater level. Evaporative cooling is slightly increased due to increased interception evaporation and transpiration of vegetation.
Green roof intensive	Intensive green roofs are implemented on all flat roofs in the area, while the roofs remain connected to sewer system	Intensive green roofs (>50cm) can store a fair amount of water in the growth medium and provide an effective reduction of total runoff and peak discharge. 14% of rainfall is stored during extreme rainfall events and up to 26% for small rainfall intensities. As the roofs discharge towards the sewer system these roofs have no effect on the groundwater level. Evaporative cooling is increased due to increased interception evaporation and transpiration of vegetation.
Water retention (on blue roofs)	Blue roofs are implemented on all flat roofs in the area	Blue roofs can store water that can be used for cooling or water usage and does not need to be discharged to the sewer system. The total roof surface allows storage of 165,000 m^3/y. As the roofs discharge towards the sewer system these roofs have no effect on the groundwater level. Evaporative cooling can be increased if water is stored on the roof instead of slowly drained.
All pavement permeable	All impermeable and semi-permeable paved surface is replaced by highly permeable pavement	Permeable pavement allows for infiltration of precipitation into the soil. It increases groundwater recharge resulting in 10 cm higher groundwater levels in summer. Transpiration increases by up to 18% due to a higher soil moisture content, which enhances evaporative cooling.
Semi-permeable pavement to permeable	Semi-permeable paved surface is replaced by semi-permeable pavement systems. Impermeable paved remains impermeable.	Permeable pavement allows for infiltration of precipitation into the soil. It increases groundwater recharge resulting in 4cm higher groundwater levels in summer. Transpiration increases by 8% due to a higher soil moisture content, which enhances evaporative cooling.
More vegetation (from 33% to 40%)	Create 40% surface area of vegetation instead of 33% by reducing paved area	More green enhances transpiration in summer up to 17%. The effect on groundwater in summer is negligible.
Disconnection roofs	All flat roofs are disconnected	Roofs are disconnected from the sewer system towards groundwater. Less stormwater runoff to the sewer system occurs and groundwater levels in summer increase. This will increase transpiration in summer up to 44%.
Increased paved surface	114% extra paved surface by reducing unpaved area	Closed paved surfaces reduce infiltration, groundwater recharge and transpiration and enhance stormwater runoff. This results in lower groundwater levels all year round (2-6cm) and less transpiration in summer (-54%).
More surface water (x2)	100% more surface water by reducing paved area	A larger area of surface water can store more stormwater runoff. Groundwater levels increase all year round (8-10 cm) as the surface water levels are higher than groundwater levels. The effect on transpiration is negligible.

3.3.5 Impact of projected changes in groundwater level on ecosystem services of green spaces

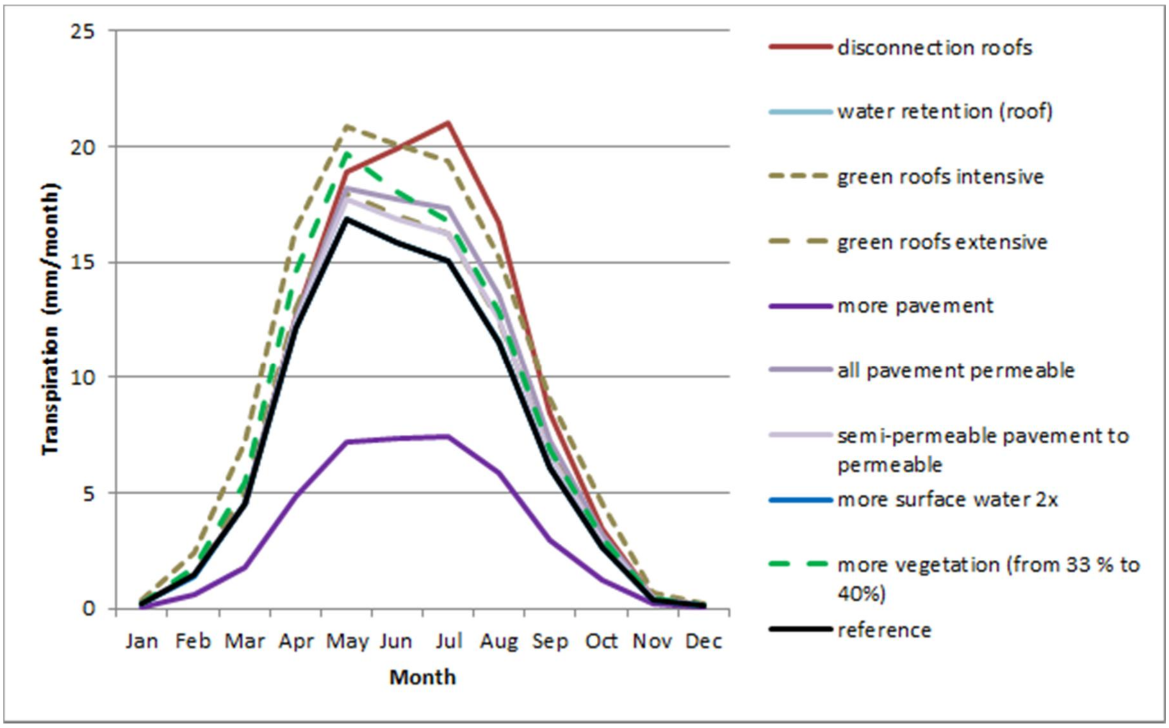
3.3.5.1 Temperature regulation (cooling)

Cooling is needed in summer and vegetation can provide this when sufficient water is available for (evapo)transpiration. In the current situation drought stress temporarily reduces the actual transpiration due to drought stress.

The results of the simulation of climate change indicate that changes in groundwater levels are limited (less than 2 cm). Land use scenarios targeted at increasing the number of disconnected roofs, and increasing the percentage of water and permeable pavements indicate that these interventions will result in higher groundwater levels of approximately 11 cm in summer. This may increase available soil moisture in summer times and lead to higher evapotranspiration rates as shown in Figure 3.8. Increase of green spaces does not influence groundwater tables. Therefore limitations as a result of geohydrological conditions to the service *cooling by evapotranspiration* provided by vegetation are not expected to worsen.

In the current situation, only 9% of precipitation is transpired in the Jaarbeurs/Station district. By adding more green elements to the area transpiration, and thereby evaporative cooling, increases. Monthly transpiration rates can increase in the area by 3 to 4 mm per month if vegetation on the ground or green roofs are added (see Figure 3.9). To determine the cooling effect on air temperature a full meteorological model should be used. Here we make an approximation based on the assumption that there is a 1 km atmospheric boundary layer in which air is mixed. If we also assume the albedo is not significantly changed we can make a very rough estimation that this results in an average daily cooling effect of almost 0.23^{o}C. Based on the relation Steeneveld (2011) made from a column model a decrease in daily avarage air temperature of 0.24 degrees could be predicted and 0.48 ^{o}C in maximum UHI reduction during the night. This is an avarega for the entire area; locally, temperatures may be lower.

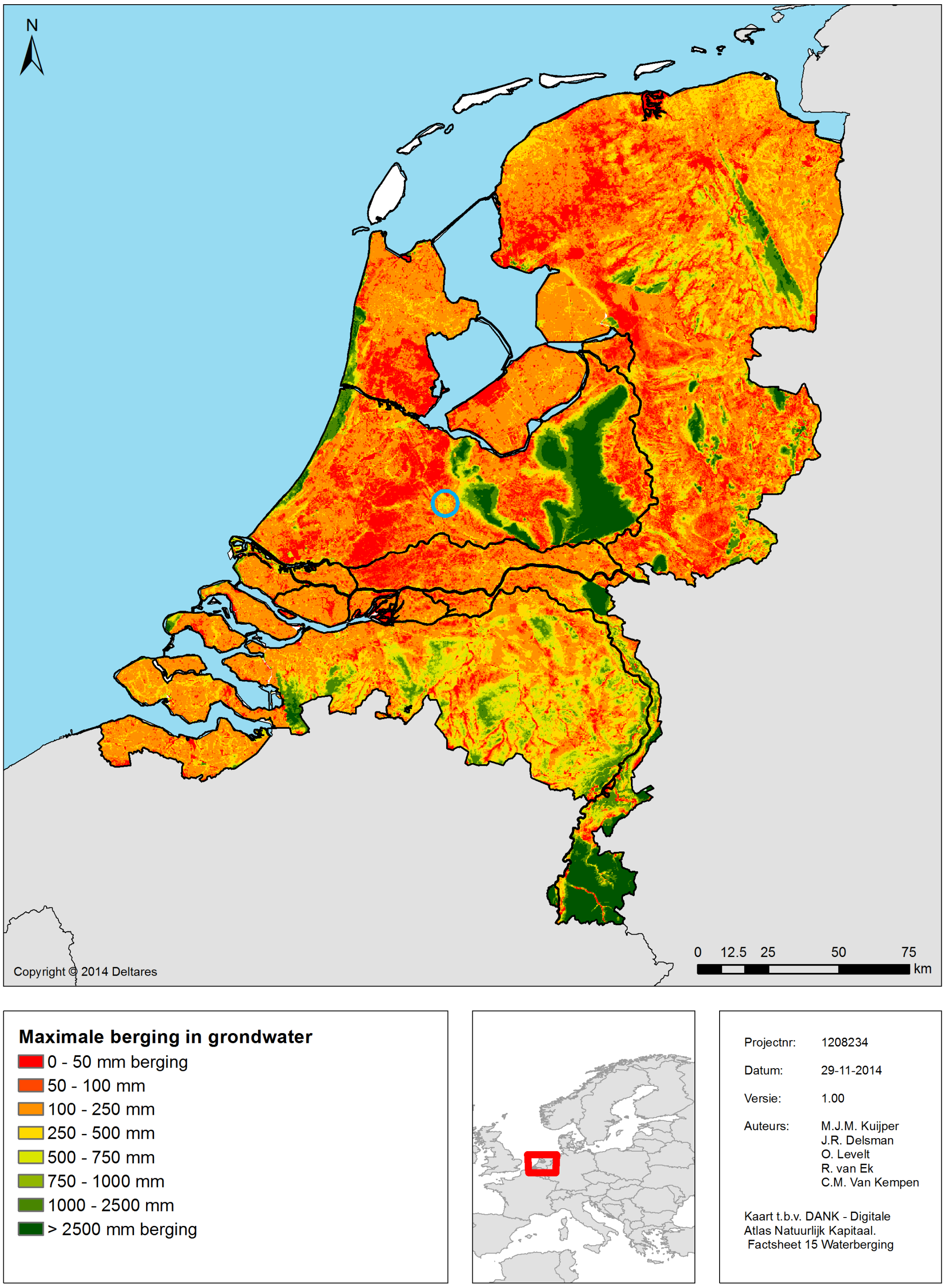
Figure 3.9 Overview of the effects of different land-use scenarios on transpiration. The curves for the reference and surface water scenarios overlap.



3.3.5.2 *Recreation and runoff mitigation*

Ponding may reduce the recreational value of green spaces. The increase in groundwater levels as a result of land use change will not lead to ponding of water on the surface as groundwater levels are still relatively deep. Deterioration of the recreational potential of green spaces is therefore not expected as a result of climate change or the assessed land use changes. Figure 3.10 shows that the soil system in Utrecht provides a potential water storage capacity that may be used to mitigate runoff; the actual drainage and storage will depend on the opportunity for rainwater to infiltrate into the soil.

Figure 3.10 The theoretical amount of water that can be stored (mm) in the subsurface, based on space: the difference between average highest groundwater table and the surface multiplied by a standard porosity (0.25). Based on NHI-model for 1998 to 2006, 250x250m model cell. The blue circle indicates the location of Utrecht. Map from www.atlasnaturalcapital.nl.



4 Conclusions

4.1 Limiting hydrological conditions for ecosystem services provision

The aim of this assessment was to explore water dependence of ecosystem services in urban green infrastructure and to assess potential bottlenecks for a district in Utrecht. A method has been developed for analysis of water availability and demand for ecosystem services provision by urban green infrastructure. The method has been applied in a case study in the city of Utrecht.

As a first step, the focus of the case study analysis is on water requirements for ecosystem services provision by green spaces only. The analysis is targeted at the ecosystem services temperature regulation (cooling), stormwater runoff mitigation, air quality regulation, noise reduction, recreation and general wellbeing and water quality regulation. In future projects, the analysis could be expanded to surface water issues and other ecosystem services.

Two relations between the potential of green spaces for the provision of selected ecosystem services and hydrological conditions seem to be most critical: 1) the impact of low groundwater table and soil moisture content on the potential contribution of vegetation on *temperature regulation (cooling) via evapotranspiration* and 2) the impact of very wet conditions, when ponding occurs, on *recreation* potential of green spaces. Besides, runoff mitigation via drainage and storage in the soil may be limited by high groundwater levels, this is however not the case in most of Utrecht.

Other relations between groundwater conditions and ecosystem services of green spaces are only relevant under very extreme and long lasting conditions such as impact on the cooling effect of shading by trees in case leaves have fallen.

4.2 Current and future impact of drought on the potential contribution of vegetation on temperature regulation (cooling) via evapotranspiration

Drought stress is identified in areas where impervious pavement is surrounding the vegetation and where the topsoil constitutes of a layer of filling sand which results in low water holding capacity.

Due to the high fraction of paved surface in the Jaarbeurs/Station district, a large part of the precipitation is drained by the sewer system either towards the surface water or towards the waste water treatment plant. Only 9% of precipitation is transpired. Due to drought stress, actual transpiration of vegetation is on average 52% of the potential transpiration during the summer period (May-August). Disconnecting roofs, and increasing the percentage of water and permeable pavement will increase infiltration of water into the soil, which results in higher groundwater levels of up to approximately 0.1 m in summer. This may increase available soil moisture in summer times and lead to higher evapotranspiration rates. By adding more green elements to the area transpiration, and thereby evaporative cooling, will increase. This could cause a daily average cooling effect of 0.24 °C decrease in air temperature and 0.48 °C reduction in maximum UHI during the night. This is an avarega for the entire area; locally, temperatures at green locations may be lower.

Based on the land use change and climate change scenarios, limitations as a result of geohydrological conditions to the service *cooling by evapotranspiration* provided by vegetation are not expected to worsen.

4.3 Current and future impact of very wet conditions, when ponding occurs, on recreation potential of green spaces and runoff mitigation

Ponding may reduce the *recreational value of green spaces*. Groundwater data for the study area do not suggest problems with wet conditions but the maintenance team of the municipality identifies ponding problems at different locations in the city. However, ponding is in most cases the result of depressions and compaction of the topsoil rather than high groundwater tables. The results of the simulation of climate change indicate that future changes in groundwater levels are limited (less than 2 cm). The predicted increase in groundwater levels as a result of land use change will not lead to ponding of water on the surface as groundwater levels are still relatively deep. Deterioration of the recreational potential of green spaces is therefore not expected as a result of climate change or the assessed land use changes. The same accounts for runoff mitigation as a result of drainage and water storage in the soil.

Recommended measures

In order to optimize the provision of *cooling by evapotranspiration* the following recommendations are provided:

- In areas with a high soil sealing grade, such as the Utrecht Centre-West/Jaarbeurs-Station district, adding more vegetation will increase the potential evapotranspiration and as a result, will reduce the temperature in summer. See Gehrels et al. (2016) for more general information on the effectiveness of green spaces for cooling and design principles for effective (multifunctional) green spaces.
- In order to reach the potential cooling, drought stress should be reduced by increasing infiltration and possibly irrigation during periods of drought.
- At this moment, the municipality irrigates trees with the aim to prevent destruction of capital. For the benefit of temperature regulation, irrigation of other types of vegetation could be considered. However, this study did not include an assessment of the effectiveness and cost-efficiency of irrigation.
- Reducing the amount of impermeable pavement, disconnecting roofs and increase of the amount of surface water (if connected to the groundwater system) are the most effective land use changes in order to improve water availability to vegetation.
- If it is not possible to increase infiltration by reducing the amount of soil sealing, infiltration measures in which runoff water is collected and infiltrated subsurface by boxes or other facilities can be applied.

In order to optimize the *recreation* services of green spaces the following recommendations are provided:

- Measures that result in lower surface runoff will reduce ponding. By enabling more infiltration of storm water in the surroundings, less water will run off towards depressions. Interventions that reduce runoff are the transformation of impermeable to (semi-) permeable pavement and unpaved surfaces or technical infiltration facilities. For example, De Jong (2015) calculated that reducing the soil sealing grade in private gardens in Tuindorp District in Utrecht would lead to a substantial increase in surface runoff mitigation (minus 15% soil sealing is plus 24% runoff mitigation).
- Measures to prevent or reduce compaction will increase the infiltration capacity of the soil. Since the groundwater level is relatively deep in Utrecht, the use of the drainage and storage capacity of the soil can be optimized in this way. Utrecht municipality already applies measures to reduce compaction such as artificial turf (grass) and special substrates.

5 References

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A Appendix 1: Urban Water Balance / Drought stress model

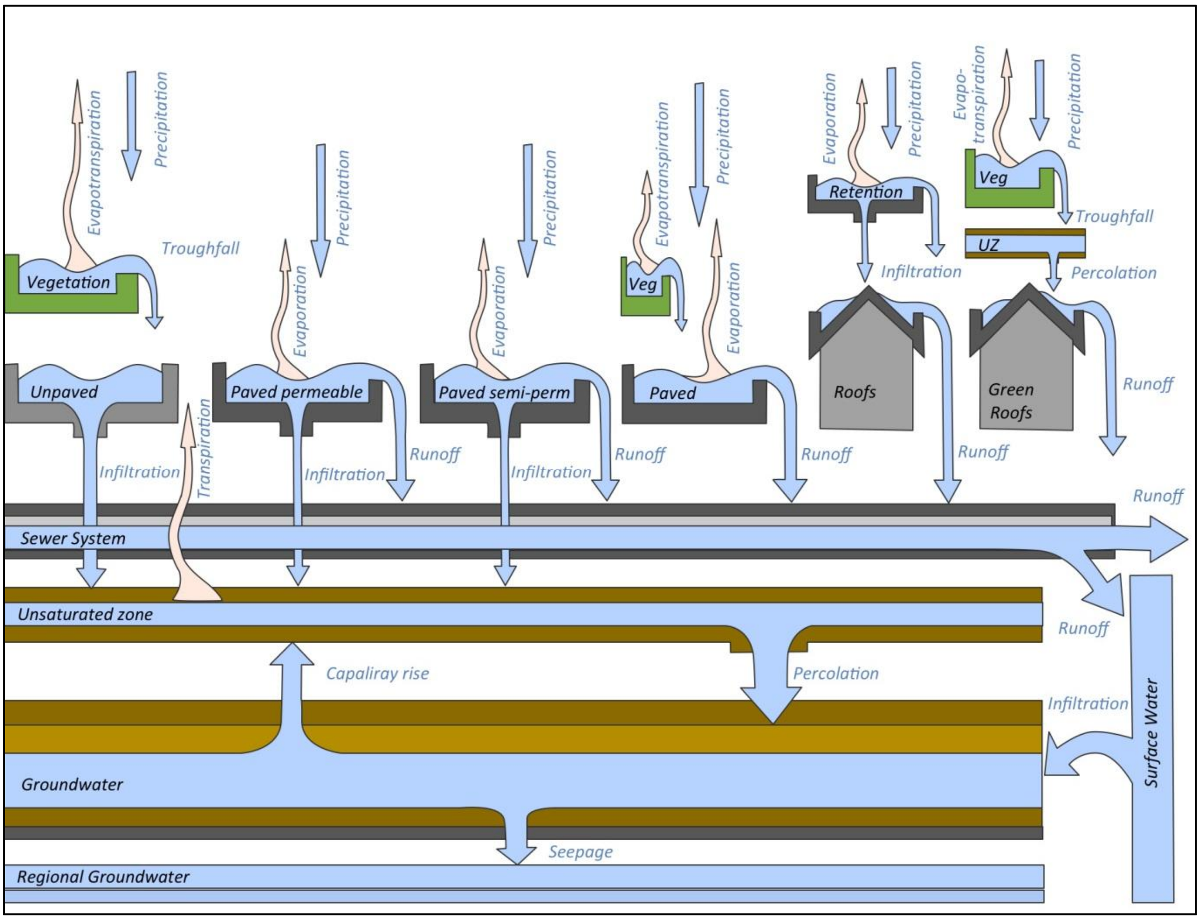
The Urban Water Balance Model (UWBM) is a multi-reservoir model to simulate both the urban water system as well as the small urban water cycle (Rutten 2013, Kuijk 2014). Within this project only water system has been simulated. The model simulates the water system at neighbourhood level at a daily time step. This time step is sufficient for simulation investigating of the effect of drought.

In the analysis for Utrecht Jaarbeurs/Station District, the model has been extended by implementing recommendations from these earlier studies. Furthermore, site-specific adjustments have been made to optimize the UWBM and to simulate land-use change effects for the Utrecht Station District case.

The UWBM is conceptualized in reservoirs and links between these reservoirs. All the reservoirs are modelled with the same concept, a linear reservoir with a defined storage capacity. Links are customized according to their function and their dependencies on state of the upstream or downstream nodes. Reservoirs and links can be grouped in different storage systems and connected to other storage systems. The number of buckets and relative fluxes may vary according to a specific situation and the actual water system. A schematization of the model as it is applied in the Utrecht Station Area is shown in Figure 1.

The model has been forced by 30 year time series of measured precipitation and potential evapotranspiration for the meteorological institute (KNMI) at de Bilt (5km away from Station area). To simulate the effect of climate change we used transformed time series that were produced by the KNMI according to the 2014 scenarios for de Bilt (Van den Hurk, 2014).
Site specific parameters of the model relate to the land use in the area, the subsurface (field capacity, conductivity and depth of the first aquifer). Other parameters are less site-specific like interception capacity of vegetation, crop factors and infiltration capacity of different paved surfaces. The site specific parameters that can be determined to sufficient precision like land use based on detailed land use maps were not calibrated. A few site specific parameters (interception storages and field capacity and conductivity of the unsaturated zone) have been calibrated using the OpenDA toolkit (www.OpenDA.org). The model has been calibrated on measured phreatic groundwater levels for 2010. Other variables that could have been used for calibration like discharge from drainage systems were not measured in the project area.

Figure 1: Schematization of the urban water balance model, as it is used for the Utrecht Station District case.



B Appendix 2: Location monitoring wells

The red circles on the map indicate the location of monitoring wells that have been used to determine average groundwater level in the study area.