university of groningen

faculty of mathematics
and natural sciences

The contribution of soil sealing in urban private gardens to runoff and urban heating

Augustus 2014

Cirsten Zwaagstra

operatie steenbreek

Science Shop

The contribution of soil sealing in urban private gardens to runoff and urban heating

Author: Cirsten Zwaagstra, BSc

Supervisors:
C.M. Ree, MSc, Bèta Science Shop, Science & Society Group, RUG
C. Visser, PhD, Center for Energy and Environment Sciences (IVEM), RUG

Requester:
Operation Steenbreek
Contact: W. Veldstra

Date: August 2014
Report Bèta 2014-1
EES-2014-201 M
ISBN: 978-90-367-7307-2

Science Shop
University of Groningen
Nijenborgh 4
9747 AG Groningen
T: 050-363 41 32
E: c.m.ree@rug.nl
W: www.rug.nl/wewi

Preface

As subjects were proposed from which to choose a subject for the learning thesis, my choice was instantly made. Soil sealing is a subject with many aspects. It concerns physical mechanisms, social aspects and policy implications. The cohesion of physical, societal and political interest leads in my opinion to a very interesting subject. It also led to many contacts and meetings, which showed me the shared concern of multiple parties, concerning the issue of soil sealing. It has been a meaningful and nice learning experience.

During the learning thesis, I have had contact with many people for which I am really grateful. First of all, I would like to thank my supervisors Karin Ree and Cindy Visser. Our meetings produced helpful information, suggestions, ideas and trust that I needed to fulfill my thesis. I also would like to thank Paul Peter Kuiper and Hans Jense for the co-operation with the Kadaster. I would like to thank Anne Helbig and Wout Veldstra (municipality of Groningen) and Cecile Lapre for their collaboration, for introducing me to boards and people whom could help me further with my research and for financing the mapping of the gardens. My thanks also to 'J en L datamanagement', whom provided me information and insight on consequences for the sewer systems; the GGD for providing their research results; Toine Vergroessen, for enlightening me about runoff models; Gert-Jan Steenveld, for his help with climate models; Floris Boogaard for his help on different perspectives of climate and water problems in urban areas; and finally members of 'Operatie Steenbreek': Edo Gies, Geert van Poelgeest, Berend van Wijk en Joop Spijker.

Contents

Summary

Soil sealing is the covering of a soil with a layer of impervious material. Impervious materials are e.g. brick, stone, plastic and concrete. Soil sealing occurs mostly in urban areas, since impervious materials are widely used there. The focus of this research is on the extent and the possible trend of soil sealing in urban private gardens. It is hypothesized that the last five to fifteen years, the sealed area in urban gardens has increased.

The soil plays a vital role in hydrology, ecology and climate, a function which is disturbed by soil sealing. The altered soil function causes increased runoff flows and flooding, increased temperatures and heat-stress during heat-waves, a loss and fragmentation of habitat and biodiversity, decreased air quality and decreased water quality.

This research aims to recognize the trend of increased sealed area and to quantify the sealed garden area. It also aims to quantify the contribution of urban private gardens to runoff and urban heating.

Three neighborhoods in Groningen were chosen: Selwerd, Professorenbuurt and Villawijk Helpman. By means of aerial photographs, the sealed area was mapped in the private areas in the years 2013 and 1998. The largest percentile increase of sealed garden area compared to the initial situation in 1998 was initially found in Professorenbuurt. However, after examination of property borders in Selwerd, large green spaces governed by the building corporation were excluded from the analysis, causing the largest increase of sealed area to be in Selwerd. The sealed area increased by 2 to 8% which is less than expected and also less compared to other studies.

The Soil Conservation Service method was used to determine increased runoff flows as a results of the increased sealed area. Calculations of the three neighborhoods in 1998 and 2013 showed increases of 0.3 to 3.4% of the runoff flows from private property. The impact of the increased runoff flow does not only depend on the increase, but also the local conditions. In Helpman, a distinct slope causes the water to drain on downslope areas. Therefore, increased runoff flows have little effect on the sewers. However, in Selwerd en Professorenbuurt it is expected that most of the runoff drains on the sewer system. The larger runoff flows will cause a higher frequency of overflows.

To simulate urban air temperatures, a micro-climate model (ENVI-Met) was used. Simulation of grass and paving in a 24 h cycle (from 6:00 to 6:00 h) resulted in elevation of the average temperature by 0.7 - 0.8 K. The orientation and the height of buildings had an influence on the average temperature. The peak of both the absolute temperature and the temperature difference was at 16:00 h. The model does not include heat storage in buildings or in paving, which causes the nighttime results to be less reliable.

Simulation of the temperature in 1998 and 2013 resulted in minimal differences for all three neighborhoods. Comparison of a 100% grass garden with a ‘100% paved garden’ scenario resulted in elevated temperatures of 0.7 K in Helpman, 0.3 K in Selwerd and 0.2 K in Professorenbuurt. The effect of these temperature rises to premature deaths is minimal, but more research is needed to accurately estimate night-temperatures.

This research shows a trend towards more sealed area in the past 15 years in the study areas. The contribution of soil sealing to runoff and urban heating could be quantified, but the relevance of the current results is difficult to assess not in the least because of questionable accuracy of especially the temperature simulations. A need for standards can be recognized, as results and relevance of soil sealing are sensitive to interpretation. How many deaths are needed to perceive soil sealing as a relevant causation? How much runoff is perceived as relevant?

However, the current study seems to imply that the physical effects of soil sealing in the case study areas in Groningen are minor. The current study results do not lead to general conclusions

about soil sealing and its consequences, because of the dependence of the physical effects on local factors as well as the non-uniform occurrence of soil sealing.

Samenvatting

Verstening is het bedekken van de bodem met een laag van ondoordringbaar materiaal. Deze materialen zijn veel aanwezig in steden, waardoor hier veel verstening plaats vindt. Dit onderzoek zal zich toespitsen op verstening in particuliere tuinen.

De bodem heeft een belangrijke rol in de stedelijke hydrologie, ecologie en het klimaat. Verstening verstoort deze functie en veroorzaakt daarmee waterinloop naar het riool, hogere temperaturen in de steden, fragmentering van habitat en een vermindering van biodiversiteit, een verminderde lucht kwaliteit en verminderde kwaliteit van het oppervlaktewater.

Dit onderzoek heeft als doel om de mate van verstening in kaart te brengen en om een eventuele trend van verstening door de jaren heen te identificeren. Daarnaast is het doel van het onderzoek om het aandeel van verstening in particuliere tuinen in verhoogde waterinloop naar de riolen en de verhoogde temperatuur te kwantificeren.

Het onderzoeksgebied bestond uit drie (deel)-wijken van Groningen: Selwerd, Professorenbuurt en Villawijk Helpman. De verstening in deze wijken is door middel van interpretatie van luchtfoto’s van 1998 en 2013 in kaart gebracht. In eerste instantie werd in de Professorenbuurt de grootste toename van verstening waargenomen. Echter, als de gebieden die beheerd worden door woningcorporaties niet worden meegenomen in de analyse verandert de versteningtrend in Selwerd aanzienlijk en is hier de toename van verstening het grootst. De toename van de mate van verstening in tuinen ligt tussen 2% en 8%. Dit is een minder uitgesproken toename dan verwacht en een minder grote toename in vergelijking met andere studies. Analyse van de mate van verstening per huizenblok laat een grote verdeeldheid in de trend zien.

Om de toename van runoff te bepalen werd de Soil Conservation Services (SCS) methode gebruikt. De berekende toename van runoff lag tussen 0,3% en 3,4% in de verschillende wijken. De directe consequentie van de toename van runoff is sterk afhankelijk van lokale factoren. Helpman ligt op een uitloper van de Hondsrug, waardoor regenwater naar de lager gelegen bieden afstroomt. In Helpman zullen vergrootte runoff-stromen niet zozeer zorgen voor een hogere frequentie van overstorten van het riool, maar wel de kans op overstromingen in het lager gelegen gebied veroorzaken. In Selwerd en Professorenbuurt kan het water minder gemakkelijk weg, waardoor vergrootte runoff-stromen zullen zorgen voor een hogere frequentie van overstorten.

Een microklimaat model (ENVI-Met) werd gebruikt om veranderingen van de lucht temperatuur als functie van verstening te modelleren. Een periode van 24 uur werd gesimuleerd van grasgebieden en geplaveide gebieden. De gemiddelde temperatuur van de geplaveide gebieden was 0.7 - 0.8 K hoger dan de temperatuur van het grasgebied. De hoogte en de oriëntatie van gebouwen hebben invloed op de hoogte van het temperatuurverschil. Het maximale temperatuurverschil vindt plaats om 16:00 uur. Het model houdt echter geen rekening met absorptie van hitte overdag en dus worden met name de nachttemperaturen onderschat.

De temperatuurverschillen tussen 1998 en 2013 van de verschillende wijken waren miniem. Vergelijking van een scenario met grastuinen met een scenario met 100% geplaveide tuinen leidt tot 0.7 K verschil in Helpman, 0.3 K in Selwerd en 0.2 K in de Professorenbuurt. Het effect van deze temperatuursverhogingen op voortijdige sterfte is minimaal.

Dit onderzoek identificeert een versteningstrend in Groningen in de afgelopen 15 jaar. Het effect van verstening op runoff en stedelijke temperaturen kon worden bepaald, maar de relevantie van deze resultaten is lastig te bepalen: deels door inaccurate resultaten en deels door het ontbreken van standaarden waar de resultaten mee vergeleken kunnen worden. Immers, bij hoeveel extra doden wordt verstening als een relevante oorzaak ervaren? En hoeveel extra runoff is relevant?

Dit onderzoek impliceert dat het effect van verstening in Groningen meevalt. Dit onderzoek lijdt niet tot algemene conclusies over verstening, omdat de consequenties van verstening erg afhankelijk zijn van lokale factoren en omdat verstening niet uniform plaatsvindt.

1. Introduction

The soil has a large variety of functions, of which the importance was underestimated until recently. The soil acts as a resource as it provides the world with food, biomass and raw materials. The soil is also a very efficient sink and it filters and transforms substances such as water, nutrients and carbon (European Commission, 2012). In addition, the soil supports landscapes of aesthetic and cultural value and it provides space for recreational purposes (European Commission, 2012).

The functioning of the soil is heavily disturbed by human activities. Agriculture, industry, tourism and urbanization all affect the soil and lead to its degradation. The impact of these activities is rather location dependent. Local conditions, climate, population density and socio-economic factors all influence the impact on the soil (European Commission, 2012).

Soil sealing in the EU

Between 1990 and 2006, the EU recorded an annual land take (the process of increasing the artificial surface) of 1,000 km^2, which is approximately the size of Berlin (Prokop *et al.*, 2011). Housing, industry, infrastructure and recreational purposes were the main contributors to land take. Land take is expected to grow, due to increasing urban sprawl, urbanization and a growing human population (Prokop *et al.*, 2011). In Europe, the share of artificial surface varies from 2% in Sweden, to 21% in Malta (figure 1.1: European Commission, 2012).

Approximately half of the artificial surface in the EU is actually sealed (Prokop *et al.*, 2011). Soil sealing is a phenomenon in which several functions of the soil are limited or destroyed. In essence, a thin layer of impenetrable substance covers the underlying soil and limits infiltration of substances through the soil. Soil sealing can either have natural causes, such as impact of rain and compaction, or anthropogenic causes, such as surface covering by roads, housing and industry (Scalenghe and Marsan, 2009).

In this report, soil sealing is defined as the coverage of a surface with anthropogenic impervious materials. Examples of impervious materials are concrete, asphalt, brick, metal, glass and plastic. Natural soil sealing is an issue in agriculture practices and is out of the scope of this research.

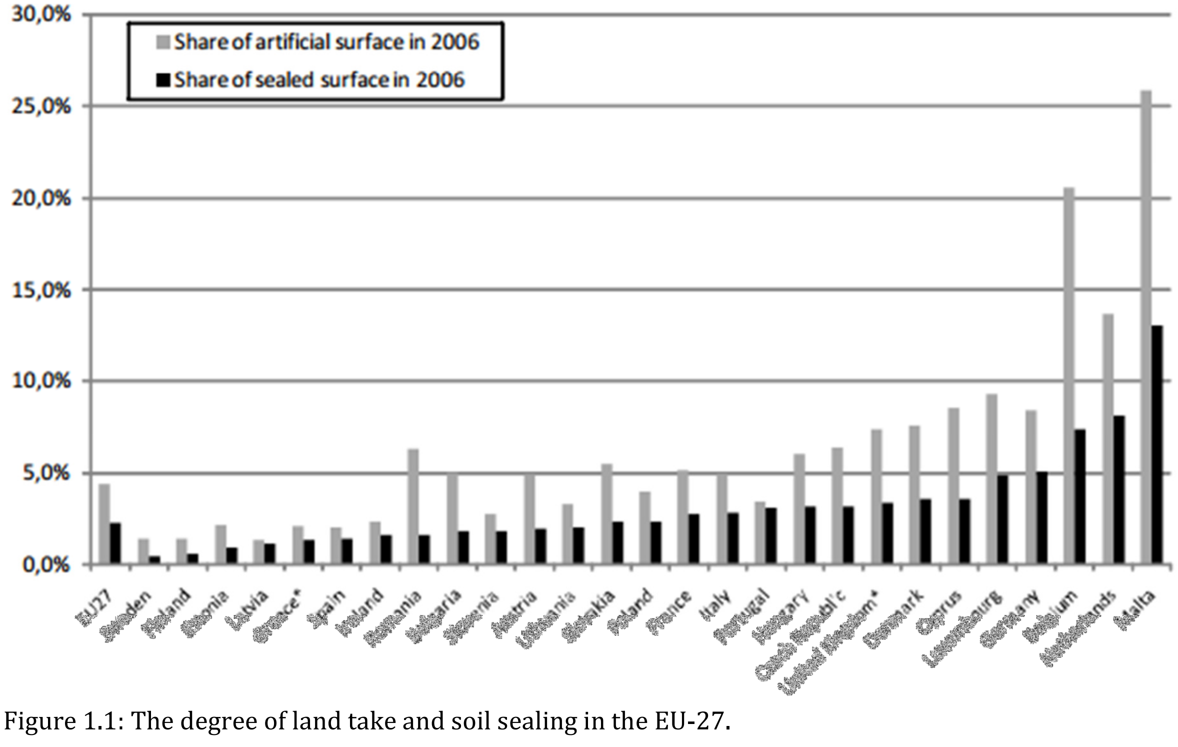

Figure 1.1: The degree of land take and soil sealing in the EU-27.

Causes of soil sealing

Soil sealing is related to population density, but other factors play a role. Behavioral changes, such as in the case of urban sprawl, and pavement of gardens have decoupled population growth from the increase of soil sealing (Scalenghe and Marsan, 2009). In several European countries, land take is growing faster than the population. Hungary and Portugal are examples of countries where land take is increasing, although the population is shrinking (Prokop *et al.*, 2011). Generally, land take cannot be used as a proxy for soil sealing, since the percentage of sealed surface as a component of land take varies among the EU member states (figure 1.1).

In addition to housing and infrastructure, pavement of gardens causes an increase of sealed surface. Pavement of private gardens is a relatively new trend, but it is growing rapidly (Perry and Nawaz, 2008). Private gardens are relatively small, but all gardens together make up a large area. The collective gardens play an important role in the urban water cycle as well as in urban ecology (Verbeeck *et al.*, 2009) and human well-being (Perry and Nawaz, 2008). The role of gardens in soil sealing is not yet or only marginally incorporated in EU soil sealing measures. However, Loram *et al.* (2009) show that gardens can make up 20% to 26% of the city's surface, which implies a serious potential of environmental impact.

More paving in domestic gardens is a growing trend throughout European countries. Several causes of this trend can be recognized. First of all, the front garden is paved to yield off-street parking. This is especially the case in areas where public space for car parking is limited (Perry and Nawaz, 2008). Car ownership grew exponentially the past decades. As a result, so did the demand for parking lots. It is noteworthy however, that Perry and Nawaz also saw a trend towards off-street parking in several neighborhoods where enough parking lots on the streets were available.

Perry and Nawaz (2008) also imply that a fashion for low maintenance gardens could be identified. The Dutch Productschap Tuinbouw (2011) highlights this fashion as well. Reasons for this fashion can be the fact that people have less time available to work in their garden. In the Netherlands, the time people spend working in their garden is declining.

Finally, also the function of the garden is slowly changing. The garden is more often used as a second living room, in which outdoor furniture, design, art and even barbeques and outdoor kitchens show up more frequently (Productschap Tuinbouw, 2011). Pavement of the garden is generally a direct consequence of this outdoor living room.

Consequences of soil sealing

The sealing of soil has serious consequences with regard to the function of the soil. Chemical reactions and the exchange of water, gasses, particles and energy between the soil and other compartments (such as the atmosphere) are disturbed and altered by a sealed surface. The modification of the functions of the soil contributes to increased runoff, urban heating, biodiversity loss and reduced human well-being (Scalenghe and Marsan, 2009).

Increased water runoff

As soil is sealed, it becomes impermeable to water flow. The seal prevents rainwater to infiltrate into the soil, which seriously alters soil hydrology. As less infiltration takes place, the soil moisture content decreases and groundwater levels will lower. Lower groundwater levels, in turn can have a negative impact on chemical reactions in the soil and cause a water deficiency in the urban area in dry seasons. Groundwater aquifers will be replenished more slowly and less water is available to vegetation and other organisms in the soil (Scalenghe and Marsan, 2009).

In addition, the volume of runoff and peak discharges will be higher as a consequence of the impenetrable surface (Verbeeck *et al.*, 2009). This will also have an impact on neighboring areas, as it increases the speed and amount of runoff to these areas, enhancing the risk of erosion and ponding.

Also, an increase in the extent of sealed surfaces has the potential to increase the risk of urban flooding (Perry and Nawaz, 2008) and to increase the pressure on sewer systems (Scalenghe and Marsan, 2009) endangering the quality of surface water. These risks will increase as heavy storms will occur more frequently as a result of climate change (Prokop *et al.,* 2011)
Verbeeck *et al.* (2009) confirm the importance of urban gardens as infiltration and retention areas. In general, sealed surfaces are applied near the street or near the house, so a large connected sealed area can be obtained.

Urban Heating

The temperature in urban areas is generally higher than in areas outside the city. These warm urban areas are also called Urban Heat Islands (UHI); the process is called urban heating. Urban heating can be defined as the difference between the temperature at a certain point in a city and the temperature at the exact same spot if the city was not there. Logically, urban heating cannot be measured directly, but is estimated using a reference point of a rural area nearby (Wolters *et al.*, 2011).
Urban heating is influenced by the increased runoff flows mentioned above, since less water is available to evaporation. Evaporation has a cooling effect as it takes energy from its environment (Wolters *et al.*, 2011). Less evaporation inevitably results in higher temperatures and enhances urban heating. Urban heating is also directly enhanced by soil sealing, because the soil and vegetation generally have a higher albedo (ability to reflect light and other radiation) than sealed surface.

Biodiversity loss

Urbanization generally results in the loss of biodiversity. Natural habitat is removed or sealed by pavement and built constructions. The remaining natural soils in urban areas are often covered with non-native species which dominate the native species. Soil sealing also leads to fragmentation of habitat of species, which leads indirectly to biodiversity loss (Scalenghe and Marsan, 2009). In addition, higher temperatures caused by built materials in urban areas affect animal and plant life. According to urban ecologist Wout Veldstra, currently several Dutch cities show higher biodiversity than their rural surroundings, caused by heavy monoculture there which illustrates the value of biodiversity in urban areas.

Air quality

Another effect of soil sealing is connected to the assumed particle and gas absorption of vegetation (European Commission, 2012). Different articles show contradicting results considering the role of vegetation in improvement of air quality. McDonald *et al.* (2007) report an uptake of NO_2 and PM_{10} by trees. They claim that planting of trees in urban areas can result in decreased concentrations of PM_{10} by 10%.
Different conclusions were drawn by the Dutch ministry (RIVM, 2011). They state that the uptake of gasses and particles by vegetation is very limited and variable, depending on the type of plant. On the contrary, RIVM concludes that the planting of trees in a street has a negative impact on air quality, as the trees cause lower wind speeds. The winds can carry away gases and particles, which are mostly produced by transport vehicles. So lower wind speeds causes the particles and gases to remain longer in the urban area.

Some literature implies a positive effect of green areas on well-being, regardless of particle and gas concentrations. Health effects of vegetation in general remain somewhat unclear unfortunately as the literature reports contradicting conclusions.

Current policy in other countries regarding soil sealing

Policy measures to prevent or mitigate soil sealing vary greatly per state as well as per region. In the UK, citizens are obliged by law to make a vehicle crossing application to the local council if they want to build an off-street parking space. However, this council does not take environmental impacts into account yet. In addition, many citizens do not submit a crossover application for paving their front-garden for parking, but prosecutions are very rare because of the costs of the court (Perry and Nawaz, 2008).

In Flanders (Belgium), current policy mitigates the increased run-off from soil sealing. All new housing developments are built with sewer systems which collect rainwater and wastewater separately (Verbeeck *et al.,* 2009). The construction of separate sewer system lowers the pressure of rainwater on the system and it prevents contamination of surface water by overflows of sewers. Literature does not report on the extent of mitigation.
Also, a planning permit is obligatory in case of construction and pavement within a garden with some exceptions. Verbeeck *et al.* (2009) studied trends in the proximity of impervious surfaces to streets and houses. They found that in most cases the impervious surfaces were added near the house or near the street. These particular surfaces are part of the exceptions for which no planning permit is required in Flanders. This finding shows that legislative measures can have a significant impact on the actions of people concerning their garden.

The EU in-depth report (European Commission, 2012) states some measures which could be implemented by the citizens relatively easily. In the case of paved front gardens to provide a car-parking space, they suggest to pave only two narrow strips for the tire tracks. This measure reduces the amount of sealing significantly. For paved gardens in general, a permeable type of paving could be used. The permeable paving can let water through thereby reducing runoff and urban heating problems. However, fragmentation issues are mitigated to a lesser extent. The permeable paving is already widely used in the UK (European Commission, 2012). However, no studies on the effects of these types of paving in the UK are known.

Until recently, the extent of soil sealing in private gardens was not investigated, neither was the impact of sealed gardens. As private gardens are often beyond the scope of planning laws, it is essential that the role of soil sealing in private gardens is to be documented (Perry and Nawaz, 2008). What is the actual extent of soil sealing in urban private gardens? What are the consequences of soil sealing in urban private gardens? These questions are important to answer in the design of accurate measures and policy to prevent and mitigate negative impacts of soil sealing.

Since urbanization and urban sprawl will continue in the future, it is important to understand the impact of soil sealing on the livability in cities. Urban heating, decreased air-quality and increased flooding potential reduce the livability in a city, but research is needed to quantify these effects.

1.1 Aim of the study

The aim of this research is to achieve a better understanding of the impact of soil sealing to urban runoff and urban heating and the contribution of soil sealing in urban gardens in particular. Soil sealing is not the only factor that causes urban heating and increased urban runoff. Modeling is needed to distinguish the effects of soil sealing in general and soil sealing in urban gardens in particular.
Quantification of the contribution of urban gardens to runoff and heating effects is essential with regard to determination of the relevance of soil sealing in gardens. A significant contribution indicates e.g. a need for (policy) measures to prevent soil sealing in gardens or to mitigate its effect.

This research will be conducted to provide, or to be part of, scientific ground to enlighten policy-makers and civilians of the negative effects of urban garden sealing. This research could therefore be of societal relevance, as the effects of soil sealing are a potential threat to the urban ecosystem and human health.

A case study will be performed on the city of Groningen, a medium-sized city in the north of the Netherlands with a representative variety of styles of urban planning. The case study can be presented as an example for other cities in the Netherlands.

1.2 Research questions

From the aim of the research, the following research question was derived:

- What is the contribution of soil sealing, in particular in urban private gardens, to urban runoff and urban heating?

The following sub-questions were defined to support the main question:

1. To which extent are gardens sealed and can a trend in time be recognized?
2. What is the effect of soil sealing in urban gardens to runoff?
3. What is the effect of soil sealing in urban gardens to urban heating?

1.3 Methods

A literature study was conducted to gain insight in the mapping techniques as well as runoff and urban heating processes. Also, a literature study was conducted to reveal the status of current knowledge in the field.
For the case-study, the Dutch Cadaster, Land registry and Mapping agency; in short Kadaster, has measured the soil sealing area in three neighborhoods in Groningen. The Kadaster used aerial photographs and visible interpretation to map soil sealing in gardens in 1998 and 2013. Their results were used for further analysis and in physical models.

Models to simulate runoff and urban heating as a function of sealed area could be found in literature. A model evaluation was done to compare the availability and applicability of the models in this research. The chosen models were used to study the effect of sealing on runoff and temperatures in general and in the three neighborhoods. Where possible, the results were compared with other studies and field data to evaluate the accuracy and relevance of the study.

1.4 Boundaries

The designed models will be physical models in which parameters of specific cases can be inserted. The models will operate at a local or street level. Urban heating effects are most relevant during hot summers. As indicated in the introduction, the effect of urban heating is the largest during these periods and so are the negative consequences to human health. Therefore, weather conditions of a hot summer day and night will be implemented in this model.
In case of the runoff model, days with heavy rainfall are the most relevant, since under these circumstances flood events are more likely to occur.

Measurements of sealed area where performed for three neighborhoods in 1998 and 2013. The use of multiple years will help to recognize trends in the extent of soil sealing in domestic gardens.
The neighborhoods exhibit different building characteristics and are therefore representable for similar neighborhoods in other Dutch cities. The chosen neighborhoods are Selwerd, Professorenbuurt and Villawijk Helpman.

1.5 Outlook

In chapter 2, current methods to map soil sealing are reviewed. Also the results of Kadaster are analyzed to assess soil sealing in the three neighborhoods in Groningen. In chapter 3, the applicability of different runoff models is discussed and a runoff model is used to calculate runoff-flows in different scenarios as well as in the three neighborhoods. Chapter 4 shows a model evaluation of models that simulate the urban climate. In addition, one model was used to simulate the temperature in several scenarios and in the three neighborhoods. Finally, chapter 5 concludes the research and gives recommendations for future research.

2. Soil sealing area measurements

Multiple studies have reported the use of techniques to map land use and land cover. A division can be made between studies using aerial photographs and studies using high-resolution satellite images. Occasionally, these data are complemented by visual inspection on location or surveys. Furthermore, a distinction can be made between different methods of interpretation. Visual interpretation can be applied to aerial photographs, satellite images and the on-site location. Automated techniques are generally applied to satellite images. GIS software is used to digitalize interpretation data. The entire study area can be interpreted or samples can be taken after which interpolation retrieves results of the area under study.

2.1 Methods to map sealed areas

Visual interpretation results in very detailed data, but is a rather time-consuming process. Interpretation of the sample or study area can (if available) be complemented by a land use or land cover map, which displays roads, buildings, water bodies and occasionally individual parcels. These maps are available at governmental Geographic departments.

Present studies identify the lack of interpretation of domestic gardens in the public maps. Garden areas are specified as ‘remaining surface’ or ‘general surface’ (Mastermap; Perry and Nawaz, 2008). However, the availability of land cover maps reduces the task of garden mapping significantly. Most studies concerning garden cover compare the impervious cover in the garden to the impervious cover in the entire study area. Since the public hard surfaces are already mapped, only the gardens need to be interpreted. In addition, information in public maps simplifies the task of identifying private area borders.

Interpretation of aerial photographs presents some challenges. Trees (though most aerial photographs are taken during spring) and buildings cause shadowed areas on the photographs which are hard to interpret. In addition, land cover patches smaller than the photograph resolution are unidentifiable. To overcome these challenges, on-site examination or street-view recordings of the study area can be used. However, the different visual means should be of the same period in time to provide a representative estimate of garden cover at that time. Estimation of land cover in the past therefore relies mainly on aerial photographs, where shadowed areas are assigned as unidentifiable.

Interpretation of gardens requires mapping of the findings. In GIS software, so-called polygons can be drawn which represent the land cover on the map. Categories can be assigned to the polygons: pervious, impervious, garden shed, etc. After interpretation and drawing, the software can calculate the total surface of the categories separately by selecting the study area. Depending on the information in the map (parcel information, categories of land cover used), statistical analyses can be performed on the study area.

Depending on the objective of the study, multiple interpretation categories and criteria can be applied. Perry and Nawaz (2008) aimed to map imperviousness in gardens in 1971 and 2004 to estimate the change in paved surface and annual runoff of the study area. They assume that only front gardens drain on the roads and thus enhance runoff. Also, they assume that the contribution of small paths from the street to the (front) door to runoff is negligible. Therefore, while interpreting, the small paths are categorized as ‘unpaved’ and a distinction between front and back garden is necessary (table 2.1).

Table 2.1: Classification by Perry and Nawaz (2008).

Category	Description	Impervious?
Impervious gardens	Significant areas of paved gardens	**Y**
Buildings	Buildings	**Y**
Other impervious	Car parks, roads, etc.	**Y**
Unpaved	Impervious areas present in 2004 but not in 1972	**N**
Front gardens	Front-, side gardens and drive ways	**-**
Back gardens	Back gardens	**-**
New development back gardens	Gardens near newly developed housing	**-**
New development front gardens	Gardens near newly developed housing	**-**

In contrast, Verbeeck *et al.* (2011) aim to investigate correlations between paving in gardens and current policy. In Flanders, to pave or build the garden a planning permit is necessary. Exceptions are the necessary pathways and driveways and terraces at a minimum distance of 1 m to the parcel borders. Correlating to the objective of Verbeeck *et al.* (2011), the classification differs from the classification by Perry and Nawaz (2008) and parcel information in the map was needed.

Table 2.2: Classification by Verbeeck *et al.* (2011).

Category	Sub-category	Description	Impervious?
House	**Terraced**	Two adjoining houses	**Y**
	Semi-detached	One adjoining house	**Y**
	Detached	No adjoining houses	**Y**
House extensions	**Solarium**	Closed enlargement to the house of glass or substitute	**Y**
	Other extensions	All other enlargements except verandas and garages	**Y**
Storage	**Garden shed**	Small shelter separately from the house	**Y**
	Garage	House to store vehicles	**Y**
Access ways	**Driveway**	Private street, min. width of a car	**Y**
	Path to front door	Connecting street with front door	**Y**
	Garden path	Private path in the backyard	**Y**
Terrace		Paved area adjoining the house	**Y**
Pervious garden		Private parcel not covered with impervious materials	**N**

Automated techniques

Automated techniques provide rapid classification of land cover, land use (change) and biodiversity and habitat mapping (Matthieu *et al.* 2007). Automated techniques generally comprise GIS integrated software (e.g. eCognition) and need high-resolution satellite imagery input (Ikonos or Quickbird; Kampouraki *et al.*, 2008).

Automated techniques in current practice can be divided into pixel-based imagery and object-based image analysis. Pixel-based imagery identifies land cover, habitat and other objects per pixel; the smallest unit of an image. The land cover represented by the pixel is identified by its spectral properties.

In object-based image analysis, first the image is divided in segments of continuous pixels, based on the spectral and spatial information of the satellite image. Identification of these segments as objects (e.g. roads, housing and water) is done by using a wide range of characteristics of the segment. Examples of these characteristics are shape, size, slope and soil properties of the segments. This technique is especially recommended in case the objects are larger than the pixels

(Mathieu *et al.*, 2007; Blaschke, 2010). In practice, also a combination of automated image segmentation and manual object interpretation can be applied (Chormanski *et al.*, 2008).

Multiple studies have used automated techniques to identify land cover and land use (Connors *et al.*, 2013; Chormanski *et al.*, 2008). However, the study by Mathieu *et al.* (2007) is the only study found thus far to have used automated techniques to map gardens. The objective of their study was to develop a methodology to automatically map the extent, distribution and density of private gardens. The methodology was then used to distinguish the role and significance of gardens in urban ecology. The classification of land cover in residential areas is given in table 2.3. Note that Mathieu *et al.*'s classification has no direct link to impervious surfaces, which is in line with their objective.

Table 2.3: Classification of residential areas by Mathieu *et al.* (2007).

Category	Description	Impervious?
Amenity pasture	Includes playgrounds and sport grounds larger than 500 m^2	**N**
Roads		**Y**
Houses	Includes residential pathways and car parks	**Y**
Garden 1	Mature and dense gardens with > 70% of the area comprising trees and shrubs	**-**
Garden 2	Open gardens with a mixture of vegetation structure elements, between 30-70% of the area comprising trees and shrubs	**-**
Garden 3	Gardens dominated by lawn, <30% of the area comprising trees and shrubs	**-**

Advantages and disadvantages of mapping methods

Both automated techniques and visual interpretation have advantages and disadvantages. Visual interpretation is time-consuming, laborious and subjective. Automated techniques are quick and objective, once the segmentation parameter settings are defined (Kampouraki *et al.,* 2008). However, automated techniques identify image objects, not real objects, which might lead to errors. For example, a partially shaded object will be identified as two imagery objects by the software (though parameter settings can avoid this particular error). Also, software is not able to intelligently include or exclude features or objects. Most importantly, though automated techniques will replace multiple processes which are currently managed by manual means, it is not yet in the stage of accurately identifying the small scale, detailed features of urban gardens (Kadaster, p.c.)

2.2 Study area and specifications

The study area consisted of three neighborhoods in Groningen: Villawijk Helpman, Selwerd and Professorenbuurt, all highlighted in figure 2.1.

The Helpman neighborhood lies on the extension of the Hondsrug, an extended hill of 70 kilometers length. Helpman and its near surroundings exhibit large surface-height differences; between 7.00 m and 0.5 m above NAP (the Dutch water level standard). The neighborhood found its origin in 1700, when the first estates were managed and became a village soon after. However, the village was swallowed by the city of Groningen in the early 20th century. The villas in the highlighted area were built in the 1950s. The area is characterized by large green areas, so-called green zones. The water bodies are of large ecological importance. Intensive rainfall therefore endangers these zones as overflow of water from the sewers flows into these water bodies. The neighborhood consists of large detached villas and large parcels.

Figure 2.1: The study areas in Groningen. Villawijk Helpman is the most southern neighborhood, Selwerd is the large western neighborhood and Professorenbuurt is the neighborhood closest to the city center (source: Google, accessed at 11-Feb 2014).

Selwerd is an area built in 1963. It is near student facilities and has multiple large apartment buildings. The rest of the neighborhood consists of attached housing blocks. At the borders of the neighborhood, ponds and ditches are part of the ecological zone of Groningen.
Professorenbuurt is part of the Korrewegwijk, which was partly built between 1870 and 1910. The Professorenbuurt itself was built in 1956 and has characteristic green spaces and courtyards. The soil consists of heavy clay, and contains contamination in some spaces. The water level varies heavily and occasionally approaches surface levels. The whole area is considered as a risk area concerning heavy rainfall. The water bodies do not contain enough capacity for storage. The water bodies are part of the sewer system for storage. The area is strongly sealed and built. The quality of the water bodies is poor, due to its storage function during overflows (Waterkaart Groningen accessed January 2014).
In all neighborhoods a mixed sewer system is present, meaning that the one sewer system copes with rainfall runoff as well as dry weather flows (e.g. water from households).

Soil cover specifications

The objective of the case-study is firstly to investigate whether a trend in the extent of impervious surface area in urban gardens can be identified in the case-study area. Secondly, the objective is to see what the effect of increased impervious surface is on runoff flows and urban temperatures. Finally, it is assessed whether the used methods were successful and possibly applicable to future studies in the Netherlands.

To fulfill the objectives, aerial photographs of the three selected neighborhoods in Groningen will be used to map urban gardens. The choice of the neighborhoods was based on availability of

sewer system data, diversity in morphology of the neighborhood, the building period of the neighborhood and the presence of private urban gardens.
Aerial photographs of 1998 and 2013 were interpreted and mapped to identify a trend concerning the impervious surface in gardens. The choice of the years was based primarily on the availability of detailed and high quality aerial photographs.

To map the urban gardens, visual interpretation of aerial photographs and manual mapping in ArcGIS were the used methods. The mapping was executed by Kadaster, the Dutch Cadaster, Land Registry and Mapping Agency. The choice of method was based on the availability of the maps, software and expertise. No interpolation will be used, because the study area is relatively small. Also, to operate physical models at the level of streets and individual parcels requires a high level of accuracy of the impervious area. Interpolation is by definition less accurate.

Classification of the identified objects in the maps will be done according to table 2.4. The categories are similar to those used by Perry and Nawaz (2008), since the objective of this study is closely related to their objective.
The choice of categories depends on the future use of the data. As physical models will be used, the resolution of the model, e.g. the level of detail, has an influence on the choice of categories. Since the results of the present study will be processed in further studies, it is important to take into account future use of the mapping results to avoid excess work load.

Two different categorization methods were chosen because of the different resolution of 2013 and 1998 aerial photographs. The high resolution photographs of 2013 (10 cm^2) will be assigned categories from table 2.4. The lower resolution photographs of 1998 (15 cm^2) do not allow clear recognition of polygons of the different categories. Therefore, 2013 will be mapped as the first step, after which the polygons of 2013 will be placed on the 1998 photographs. Finally, each polygon of the 1998 photograph is interpreted to assign a percentage of the extent of sealing. Table 2.5 shows the different percentile categories; the percentages indicate unpaved areas.

Table 2.4: Classification in the case-study Groningen 2013.

Category	Description	Impervious?
1	Dwellings with attached sheds	**Y**
2	Detached garden sheds	**Y**
3	Paved area	**Y**
4	Unknown	**-**
5	Unpaved area	**N**
6	Small garden paths	**Y**

Table 2.5: Classification in the case-study Groningen in 1998.

Category	Percentages unpaved	Average unpaved
A	0 – 5%	2.5%
B	5 – 35%	20%
C	35 – 65%	50%
D	65 – 95%	80%
E	95 – 100%	97.5%
F	Unknown	Unknown

2.3 Results and discussion of mapping in Groningen

The tables below show respectively the extent of sealing of private property and the increase of sealing as a percentage of the total private area. Also shown is the extent of non-sealed areas and the unidentifiable areas, classified as unknown (not present in the Helpman neighborhood). The mentioned values in the first three (two in Helpman) rows account for the total private property area which includes sealing by houses. In the last rows, the housing area is excluded. The range in the 'change' column is a result of the unknown category. All values exclude the municipal areas, e.g. roads, water bodies, common greens and sidewalks.

Table 2.6: Areas calculated according to the output of the Kadaster (as calculated in Appendix A).

HELPMAN	2013	1998	Change
Total paved area	77122 m^2 (37.8%)	73021 m^2 (35.8%)	2%
Non-paved area	127077 m^2 (62.2%)	131179 m^2 (64.2%)	
Paving per parcel	334 m^2	316 m^2	
Paving per garden	197 m^2	189 m^2	4.1%

PROFESSORENBUURT	2013	1998	Change
Total paved area	106010 m^2 (77.8%)	100509 m^2 (73.8%)	2.7 - 6.0%
Non-paved area	27454 m^2 (21.2%)	33815 m^2 (24.8%)	
Unknown area	2714 m^2 (2.0%)	1854 m^2 (1.4%)	
Paving per parcel	129 m^2	125 m^2	
Paving per garden	55.1 m^2	51.1 m^2	3.3 - 14.3%
Unknown in garden	3.3 m^2	2.3 m^2	

SELWERD	2013	1998	Change
Total paved area	188090 m^2 (70.0%)	178348 m^2 (66.4%)	2.8 - 3.6%
Non-paved area	80634 m^2 (30.0%)	88307 m^2 (32.9%)	
Unknown area	59 m^2 (0.0%)	2130 m^2 (0.8%)	
Paving per parcel	146 m^2	138 m^2	
Paving per garden	62.5 m^2	57.6 m^2	5.4 - 8.4%
Unknown in garden	0 m^2	1.7 m^2	

Table 2.6 shows large differences between the studied neighborhoods. In Helpman the total sealed area was 35.8% in 1998 (including housing area) compared to 37.8% in 2013; 2% of the total area was transformed to sealed area in 15 years. In Professorenbuurt, transformation of the neighborhood area was more severe: 2.7% to 6.0% of the total area was sealed in 15 year, compared to 2.8% to 3.6% in Selwerd.

Also comparing the total sealed in area in 2013 shows large differences. Helpman is the least sealed (37.8%), while Professorenbuurt is the most sealed (77.8 - 79.8%). The different sealing percentages are partly due to garden paving, but also due to sealing by houses. Table 2.7 shows the average parcel area, housing area and garden area in 2013 for each neighborhood. Helpman exhibits the largest parcels and the smallest relative housing area which explains the small sealing percentage compared to Professorenbuurt and Selwerd.

Table 2.7: Average parcel size, housing area per parcel and garden area per parcel in 2013.

	Helpman	Professorenbuurt	Selwerd
Parcel area	884 m^2	168 m^2	208 m^2
Housing area	137 m^2	73 m^2	83 m^2
Garden area	747 m^2	95 m^2	125 m^2

In Table 2.6, the largest uncertainty margin is found in Professorenbuurt. The high building density in this neighborhood causes shading effects, which limits the extent of identification of this area.

In Selwerd there are large green spaces, managed by housing-corporations. It is debatable whether these areas should be included in analysis of private gardens. Since these corporation areas take up a large area and remain the same in 2013 compared to 1998, they reduce the change in the extent of soil sealing in the results. In addition, front gardens in Selwerd have been left out of the analysis by the Kadaster because according to the Dutch register these gardens are municipal property. After visual examination, suspicion arises that the majority of the front-gardens in Selwerd are either private property or at least managed by the renters or owners of the house.
Due to time limitations, the front gardens could not be added to this research. However, examination of the corporation green spaces and flats resulted in the exclusion of a considerable area (table 2.8).

Table 2.8: Calculated areas in Selwerd after correction for corporation areas.

SELWERD	2013	1998	Change
Total paved area	95145 m^2 (85.0%)	86117 m^2 (76.9%)	6.6 - 8.1%
Non-paved area	16766 m^2 (15.0%)	24256 m^2 (21.7%)	
Unknown area	59 m^2 (0.0%)	1597 m^2 (1.4%)	
Paving per parcel	112	101	
Paving per garden	52.3	41.7	20.0 - 25.6%
Unknown in garden	0.1	1.9	

By excluding the corporation property, the increase of total sealed area rises from 2.8 - 3.6% to 6.6 - 8.1% and the increase of sealed area in the garden changed from 5.4 - 8.4% to 20.0 - 25.6%. This shift in the results shows the importance of examination of property borders in order to identify accurate trends of soil sealing in private gardens.

In Selwerd, after excluding corporation property, 51 housing-blocks were identified. The increase of sealed area ranged from -15.8% to 34% (table 2.9). In Professorenbuurt, 13 housing blocks are identified and sealing increased from 1.7% to 28.5%. In Helpman, 10 housing blocks or regions were identified were sealing changed by -5.3% to 30.3%. In both Helpman and Selwerd, a small number of housing blocks show negative trends: soil sealing declined over the years.
The extent of soil sealing and the change of sealed area are not uniform within the city of Groningen, nor within the studied neighborhoods of Groningen. Chapter 3 and 4 will examine if the models can identify a different extent of physical impact in the housing blocks.

Table 2.9: Range of increase of sealed area.

	Range of increase
Helpman	-15.8 - 34%
Professorenbuurt	1.7 - 28.5%
Selwerd	-5.3 - 30.3%

Table 2.10: Comparison with other studies.

Change in studies	Change of total paved area	Increase of paved garden area
Helpman	2%	4.1%
Professorenbuurt	2.7 - 6%	3.3 - 14.3%
Selwerd	6.6 - 8.1%	5.4 - 8.4%
Perry and Nawaz	12.6%	138%
Verbeeck *et al.*	18%	-

The calculated trend of sealing is less severe than expected, comparing the results to the results of studies in Leeds (Perry and Nawaz, 1998) and Flanders (Verbeeck *et al.*, 2011; table 2.10).

Perry and Nawaz (2008) investigated aerial photographs from 1971 and 2004 of a suburb in Leeds, UK. Verbeeck *et al.* (2011) investigated private gardens in 5 neighborhoods and compared the original building plans (i.e. bare soil) to the impervious gardens in 2008.

Multiple causes can be the explanation of deviation between the three different studies. Firstly, all three studies used different methods, since Verbeeck *et al.* (2011) compared the current situation with original buildings plans. Perry and Nawaz (2008) were able to draw polygons in both 2004 photographs and in the photographs of 1971 (surface resolution of 60 cm^2). In this study, the photographs of 2013 were interpreted in a similar manner, but the photographs of 1998 were interpreted in a different way (see paragraph 2.2).

Also, the trend of sealing may not show linear behavior in time and therefore comparison with different timelines is difficult. Also, the trend of sealing might depend not only on the dates of the study and thus the 'fashion' of that period. The age of the neighborhood in general could play a role in the extent of sealing. As a house is only just built, it is generally sold without paving. Therefore, comparing the situation of a young neighborhood with 15 years later can result in drastic changes, as was the case in the study of Verbeeck *et al.* (2011).

In addition, the trend of sealing cannot be compared with other countries, possibly because of other legislation, different neighborhood characteristics, different culture and different social behavior.

Finally, in several cases in Groningen the front garden was not taken into account, because it was not private property though it seemed the citizens were influencing the outlook of the garden. The exclusion of front gardens is expected to result in a lower increase of sealing areas than the actual trend.

Discussion method

It has become clear that the results depend largely on the specifications. Interpretation of only gardens within private borders has led to the exclusion of gardens which either have a vague property-border or are municipal property but are managed by the renters or owners of the house.

In addition, large properties managed by housing corporations are included in the interpretation analysis, because these areas are not municipal property and are therefore labeled as private area in the registers of the Kadaster. These areas are generally not managed by the inhabitants of the neighborhood. Therefore, inclusion of these areas will bias the results when aimed at identification of the trend of soil sealing in private gardens. However, as municipalities need to assess runoff flows regarding sewer-system capacity, all areas should be interpreted. Therefore, a semi-private category could be introduced. In that case, all areas are interpreted for runoff analysis and exclusion of corporation areas from the garden trend analysis is easily manageable.

Shading effects give rise to an uncertainty margin. However, it is questionable whether these uncertainty errors could be improved as no high-resolution aerial photographs of past years of Groningen are available. This also raises the question whether automated techniques can be employed in the near future to interpret old material. Another option to investigate differences between current situations and past is to compare the latest maps with the original building plans. This method will show the accumulative increase of sealing but it shows little of the trend. Sealing could have occurred in any period of time and it does not prove that sealing of gardens is an issue of the latest 5 to 15 years.

The interpretation method of the 1998 aerial photographs also limits proximity analysis of sealed garden areas as was done by Verbeeck *et al.* (2011). Proximity analysis can be useful for social studies about correlation between the location of increased sealing and possible motives for sealing the garden.

With the current method, no differentiation can be made between fragmented sealed areas and connected areas in 1998. For thorough sewer inlet calculations, information on connected sealed areas is needed to estimate which areas drain on the sewers and which areas drain on unpaved garden areas. The 1998 situation does not allow this thorough examination and thus only rough runoff estimations can be done to compare 1998 and 2013.

2.4 Key findings

The largest percentile increase of sealed garden area compared to the initial situation in 1998 was initially found in Professorenbuurt, but after examination of property borders in Selwerd. The hypothesis is that – on neighborhood scale - the current sealing trend will cause the largest physical effect in Selwerd, followed by Professorenbuurt, while Helpman will encounter the least problems. In addition, housing blocks within the neighborhoods showed large differences concerning the increase of sealed area. In the next chapters, simulations will test the correctness of these statements. Also, the relevance of the calculated sealing trend will be tested in the next chapters as simulations will show the expected physical impact in the neighborhoods.

3. Precipitation runoff

The hydrologic cycle

The generation of runoff is part of the hydrologic cycle (figure 3.1; Chow, 1988). The hydrologic cycle describes the circulation of water between Earth and atmosphere on a global scale. The water cycles by the continuous processes of evaporation, condensation, precipitation, infiltration in the soil, interception by vegetation, seepage (groundwater recharge) and surface, sub-surface and overland flow. The rate of these processes depends on vegetation, weather patterns, topography as well as human activities e.g. soil sealing. Chow (1988) divides the hydrologic cycle into processes occurring in three separate systems: the atmospheric system, the surface system and the sub-surface system. Runoff is part of the surface system; it is the flux of rainfall which does not infiltrate into the soil nor is intercepted by vegetation (also called rainfall excess). The overland flow of surface runoff occurs when the soil is sealed, saturated or when rainfall intensity is higher than infiltration speed.

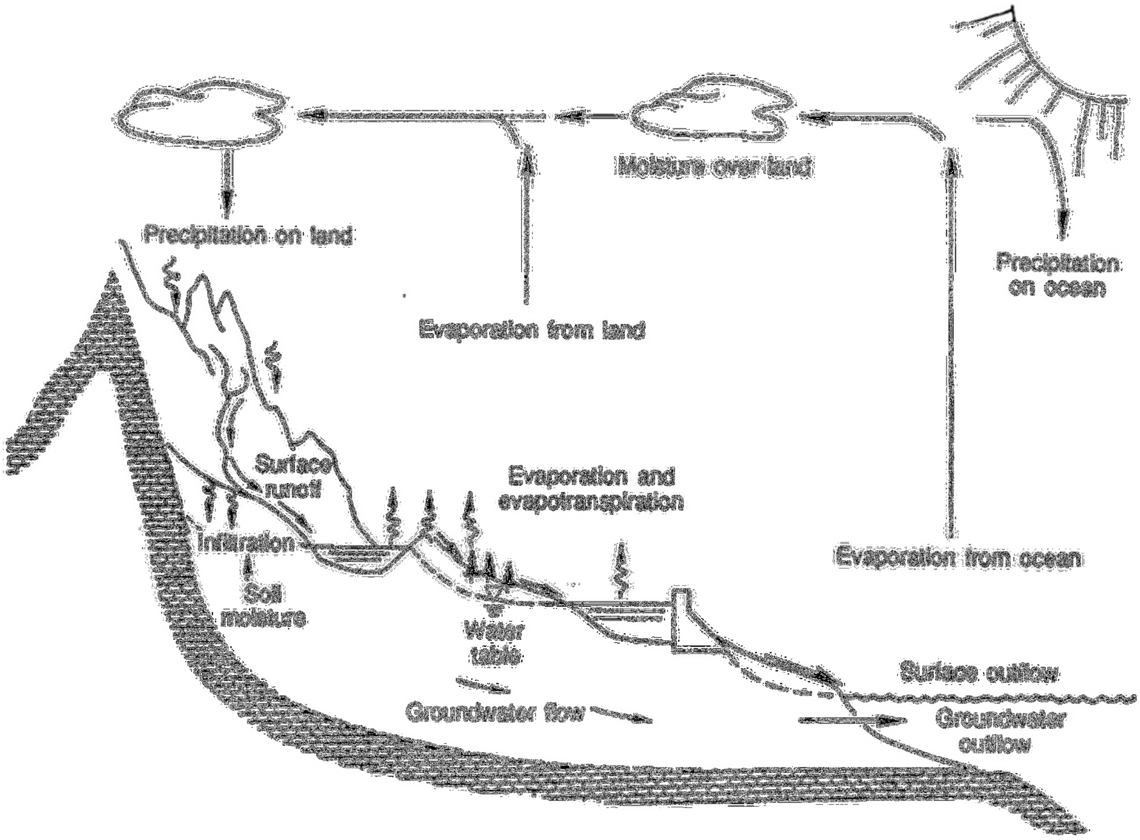

Figure 3.1: The hydrological cycle (Chow, 1988).

3.1 Runoff mechanisms

The amount of rainfall excess or surface runoff depends on rainfall intensity, the infiltration capacity and the presence of vegetation. The infiltration capacity of the soil varies for the different soil types and is additionally influenced by the antecedent moisture conditions and land cover.

In general soil sealing reduces the infiltration capacity of the soil, therefore increasing the amount of runoff. Also, excess rainfall flows more rapidly across smooth sealed surfaces, compared to rough vegetated surfaces, which is in accordance with Manning's equation (Manning's equation states that the velocity of the water flow is proportional to the roughness of the land surface; Jacobson, 2011).

Accordingly, infiltration and travel time are reduced, both resulting in increased peak discharges and runoff (Jacobson, 2011). Slope, length of the flow path, depth of the flow path and roughness of the surfaces all influence the travel time (TR55).

Some studies argue the existence of a threshold level of imperviousness below which changes in surface runoff flows are not distinct. The level of this threshold varies between 3 - 20% impervious cover (Jacobson, 2011). Also, the existence of a threshold is not agreed upon by all authors (Jacobson, 2011).

Impact of soil sealing

Since increased impervious surfaces cause storm runoff flows to increase in volume and speed, soil erosion and (downstream) flooding could be the result (TR55). In addition, less infiltration and seepage in areas with large sealed areas suffer decreases in groundwater recharge (Brun, 2000). The groundwater recharge is necessary for residential water supply and the health of local soils and the life they support (Harbor, 1994). Reduced groundwater recharge is a long-term effect of an increase of impervious surface area. Flooding is mostly a complication of short-term impact due to increased sealed soil combined with heavy rain events (Bhaduri, 2000).

The increased peak discharge during heavy rain events increases the load to sewer and drainage pipes, increasing the possibility of overflows. In addition, in the case of a mixed sewer system (i.e. draining of runoff and dry weather flows in one system) the increased runoff flows increase the pressure on water treatment facilities.

The increased runoff flows wash more of the soil, dust and debris from impervious surfaces, causing pollutants to reach more readily the surface waters. Pollutants in urban runoff are one of the major causes for surface water contamination (Brun, 2000).

Implications for modeling

To estimate runoff in relation to soil sealing either physical measurements need to be performed or a model has to be used. Jacobson (2011) states that stream-flow records are not reliable for identifying trends caused by impervious surfaces, because of climate and background variability. Also, it is discussed by Huber and Dickinson (1988) that gauging stations measure runoff from an area typically larger than the study area except when the study area covers the entire watershed. Therefore, the most reliable means to indicate runoff is by computer simulation.

Generally, there is a difference between total impervious area (TIA) and directly connected impervious area (DCIA). DCIA is area directly connected to a drainage or sewer system. The remainder of the impervious area (ineffective impervious surface) routes runoff on pervious surfaces. Quantification of DCIA and TIA is difficult, since the distinction of DCIA might be related to the extent of rainfall (Jacobson, 2011). In addition, paving slabs let some water seep through their cracks, increasing the infiltration capacity of ‘impervious’ surfaces, which makes it more difficult to accurately estimate the effective impervious area (Perry and Nawaz, 2008).

Since soil sealing has both long-term and short-term impacts, it is important to perform assessments on both time scales. The impact of soil sealing can be simulated regarding a single event, i.e. a heavy rain storm, to assess the increased risk of flooding and overload to sewer and drainage systems. In addition, long-term assessment of the impact of soil sealing can be performed by simulating runoff for multiple years. In this way, the effect of soil sealing on groundwater recharge and the increased load on water purification facilities can be illustrated (Bhaduri et al, 2001).

3.2 Runoff models

General model objectives

Mathematical runoff models are available in large numbers, all comprising different objectives and computational methods. Several of these models have been reviewed by Zoppou (2001), and Jacobson (2011), but a complete overview is not available since over 100 models have been designed (Zoppou, 2001). Therefore, the different classes of models will be discussed here as well as examples of models to find a match with the objective of this research.

In general, four objectives of urban runoff models can be identified: screening, planning, design and operation. The characteristics of these models both differ widely as well as overlap to a certain extent (Huber and Dickinson, 1986). The methods of the simplest models are often the fundament of the complex models.

Screening models are the simplest of the models and are meant to provide a first estimate of the runoff problems and can be computed by a simple calculator.

Planning models require a minimum of data and generally have a low mathematical complexity. Planning models can be used by planners or policy makers to assess the response of the watershed to changes in land-use.

Design models can process smaller time steps. These models can be used to design sewer or drainage systems as well as flood control systems. The data requirement varies, but ranges from moderate to extensive. The routing of water and pollutant flow through the urban area can be described by these models.

Operational models aim to control decisions during flood and storm events. These models are highly sophisticated. They incorporate system response to flood control systems and advise the operator during events.

Model categories

Within the different objective-based categories, another categorization can be recognized according to mathematical or hydro-meteorological characteristics (Feldman, 2000):

- Conceptual or empirical models
- Distributed, semi-distributed or lumped models.
- Continuous or single event models
- Deterministic or stochastic
- Measured-parameter or fitted parameter

The distinction between conceptual and empirical models concerns the knowledge on which the model is built. Conceptual models are based on knowledge of the physical, chemical or biological processes. Empirical models are based on observations and do not specifically represent the process itself.

The choice of a model within the remaining categories depends both on the available input data and on the desired output of the model. Distributed models consider spatial variations of characteristics and processes in a watershed. Lumped models ignore or average spatial variations. Continuous models simulate longer periods, typically of a year or longer, while event models simulate a single storm which can take a few hours to a few days. Deterministic models require input, parameters and processes of known certainty, while stochastic models comprise a description of random variation. Finally, in a measured-parameter model the model parameters can be measured; the input. In fitted parameter models, the input parameters cannot be measured and thus, the parameters are found by changing the parameters to fit the output with observed values (Feldman, 2000). A choice in these two categories is thus strongly dependent on the available input and output data.

Regardless of the mathematical distinction of models, some of the evaluated models are distinctly more applicable to either large scale or small scale cases. Also, several of the models are aimed to simulate either urban or more agricultural areas.

The aim of the current study is to estimate runoff depth as a function of the change in soil sealing in urban gardens. The choice of the model is dependent on a match between model objective and the study objective as well as data availability.
The study objective relates mostly to screening or planning models added up by a need for a model that does not require calibration and requires a minimum of input data. Finally, if available a model aimed at small scale and urban estimations is favored.

Evaluation of models

In this report, eight models are examined. These models were chosen because of the amount of case-studies they were used for (the model has been evaluated thoroughly). Table 3.1 shows the different models and the objective of the case-study it was used for, the needed input of the model, the output of the model and the references of the case-studies.

Table 3.2 shows a comparison of the models. Dark colors indicate that the indicated characteristic is present. The models are tested according to their free (online) availability and their applicability to the case-study in terms of fitness to the case-study area (urban area). The table indicates whether calibration is needed and whether the model simulates events or long-term averages and whether the model exhibits spatial variance.

Numerous hydraulic models are available to calculate runoff as a function of paved surface area. However, most of the demonstrated models aim to simulate more than runoff production. As a result, the models are complex and require multiple input parameters.
In this research, the aim is to make a first estimation of the impact of soil sealing in private gardens to runoff flows, so no routing calculations are required. Therefore, a simple model is sufficient to do the calculations.
In addition, calibration of the model is not possible. Rainfall is not uniform in the city which causes a deviation as the rainfall data are based on the meteorology station in Eelde (KNMI). No trend has been recognized yet considering rainfall in the city since gauging stations were only able to measure rainfall accurately for a short period of time (J en L datamanagement, 2014). Satellite rainfall measurements were not available to this study.
Multiple authors emphasized the essence of calibration of the model, when required. Therefore, the empirical SCS method was chosen to calculate runoff. Also, the simplicity of an empirical relation and the minimum input required, matches the simple estimation required for this study. SCS is used in multiple case-studies in the U.S. as well as in Europe and is the base of multiple larger models or computer programs. It is therefore regarded reliable for a first estimation of runoff in this study.

Table 3.1: An overview of the evaluated models

Model	Objective model/case-study	Input	Output	Case-studies
ABIMO	Raise understanding of the impact of urbanization on hydrology	Slope, ground water level, sealing area, soil type, grain size	Runoff, actual evaporation, groundwater recharge	Haase, 2009.
STORE DHM	Simulate hydrologic processes based on storage release approach in large watersheds	Soil data, flow direction, flow length, slope, land cover data, rainfall, gauged data from the flow channels	Peak flow, peak time, runoff coefficient	Kang and Merwade, 2011.
SCS Harbor	Provide a simple method for planners to estimate long-term runoff and groundwater recharge as a function of land-use	Long-term precipitation, land-use map, soil map and TR55 to determine the curve number	Runoff depths, though preferably reported as a percentage of change in runoff	Harbor, 1994
HSPF	Simulate the hydrologic and water quality processes for extended periods of time. Used to assess the effects of land-use change, flow diversions, reservoir operations etc.	daily precipitation, daily potential evapotranspiration, air temperature, land cover, soil type, slope, channel-parameters and reservoir-parameters. field data base-flow or runoff	Soil moisture storage and daily stream flow toward the gauging station	Brun and Band, 2000.
SWMM Level 1	Use a simple method to estimate runoff quality and quantity to help decision making en reduce costs	Annual precipitation and percentage of impervious area are needed	Annual runoff	Heaney *et al.*
SWMM	Calculate urban runoff quantity and quality and simulate flows through sewer and drainage system and control systems	Rainfall data, parameters describing the catchment, storage capacity, conveyance and treatment of the flows	Runoff, runoff flows through sewer systems and effect of control system on flows	Park *et al.*, 2012
SDDH	Simulate urban runoff taking into account temporal and spatial variability to estimate the response of a catchment to storms	Roughness coefficient, precipitation data, land cover data, topographic data, calibration data	Streamflow hydrographs	Melesse and Graham, 2004
SOBEK	Calculate runoff by multiple methods and routing. Design of sewer-systems	Precipitation, infiltration capacity, soil type, seepage coefficient, slope, paved and unpaved area	Surface runoff, storage,	Used in most Dutch municipalities

Table 3.2: The evaluated models

Model	Available	Fits case-study	Needs calibration	Event	Continuous	Lumped	Distributed
ABIMO					■	■	
STORE DHM			■	■			■
SCS	■	■		■	■	■	
HSPF	■		■	■	■	■	
SWMM Level 1	■	■			■	■	
SWMM	■		■	■	■		■
SDDH	■		■	■	■		■
SOBEK-RR	■	■	■	■	■	■	■

3.3 Modelling results

Save from the extent of sealed area, runoff generation depends on several factors. These parameters include the groundwater level, the soil type, the type of vegetation in the unpaved regions and the extent of seepage and infiltration through the soil. The SCS method allows adjustment of the sealed area, while almost all other parameters are integrated in the Curve Number (CN). Adjustment of the antecedent moisture conditions in the relations provides another means of expression of the parameters.

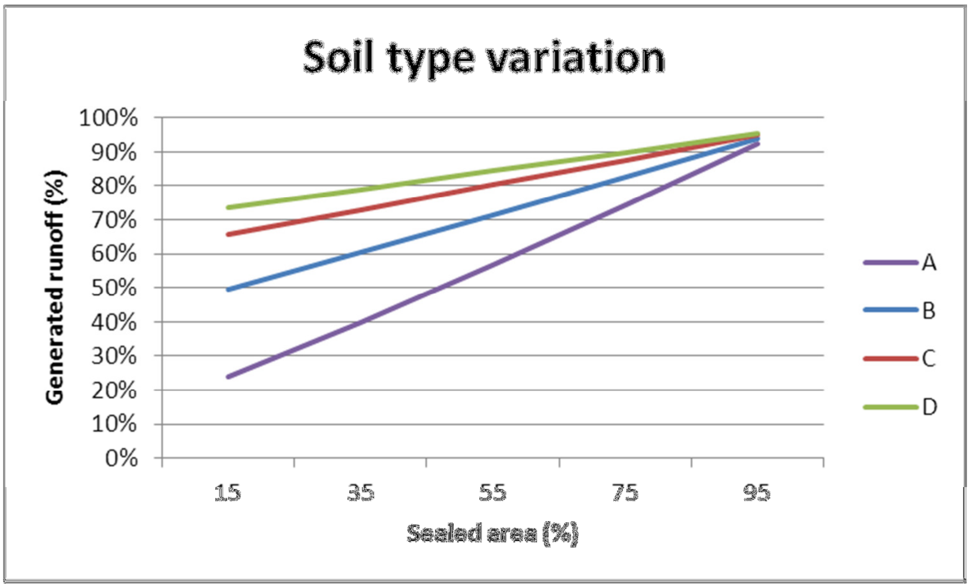

Figure 3.2: The variation of runoff according to sealed soil percentage and soil type. Soil A is sand, loamy sand or sandy loam. Soil B is silt loam or loam. Soil C is sandy clay loam and soil D is clay loam, silty clay loam, sandy clay, silty clay or clay. All calculations were executed using average antecedent moisture conditions and a 19.5 mm rainfall event.

First, runoff was calculated for areas with different percentages of sealed cover as well as different soil types: A, B, C and D (see figure 3.2). The calculations illustrate that soil sealing has the greatest influence on soils with large infiltration and storage capacity (soil A), whereas runoff flows from clay and loamy soils change less as the soil is more sealed. However, the absolute amount of runoff from gardens (if not 100% sealed) is larger in areas with soil with low storage and infiltration capacity, which is as expected.

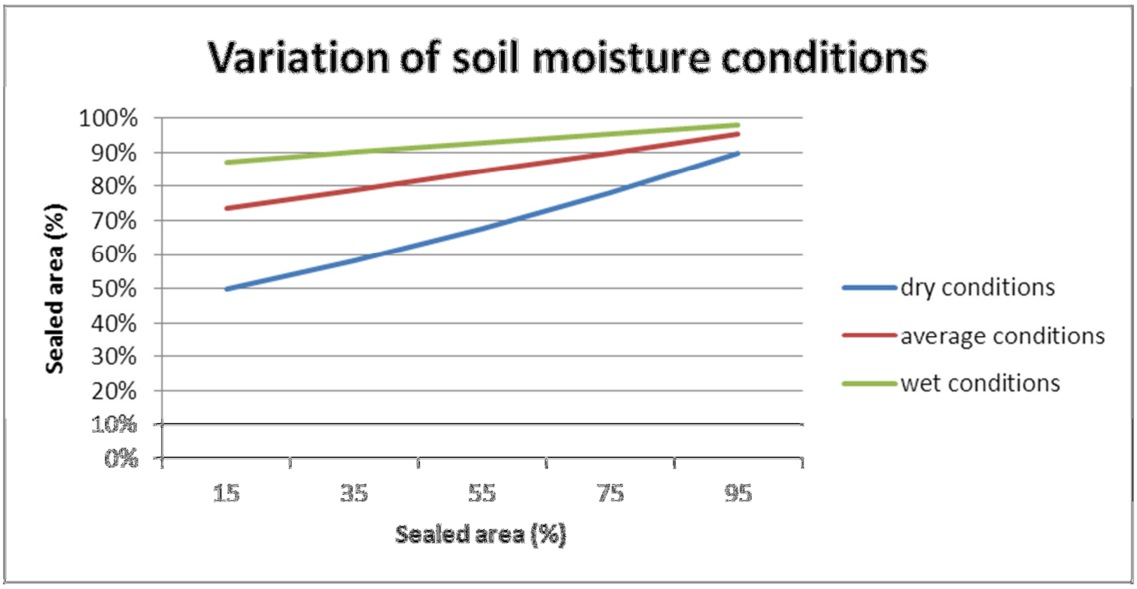

Figure 3.3: The variation of runoff according sealed soil percentage and antecedent moisture conditions. All calculations were executed using soil type D and a 19.5 mm rainfall event.

Figure 3.3 shows calculations of runoff according to different antecedent moisture conditions. Since the antecedent moisture conditions are also influential to infiltration and storage capacity, a similar trend can be recognized. Dry soils (AMCI; Pandit and Gopalakrishnan, 1996) are less saturated and are able to take up more rainfall, thus soil sealing has a larger impact in these circumstances. Wet soils (AMCIII) are highly saturated so the runoff-flows are relatively large although little sealing is present.

Previously mentioned calculations accounted for an event of 19.5 mm rainfall. As the amount of rainfall in the model is lowered, the values in these calculations change though the trends remain the same. Smaller events are more easily absorbed by the soil and thus the difference in runoff production between sealed soils and unpaved soils is larger than in the case of heavy storm events.

Case-study results and discussion

To calculate runoff in the three neighborhoods, a rainfall event of 19.5 mm was simulated. The soil type D was chosen for all neighborhoods since the deeper layers of Groningen all consist of clay. Also, Perry and Nawaz (2008) argue that the compact soil in urban areas in general can best be described by soil type D. In accordance with Perry and Nawaz (2008), a CN of 80 was chosen for unpaved gardens and a CN of 98 was chosen for the sealed area. The sealed areas incorporated in the simulation are as calculated in chapter 2.3. To calculate runoff in Selwerd, the total mapped area was chosen, including the corporation areas.
The runoff calculations of the neighborhoods are shown in table 3.3. The table shows the change in runoff flow in 1998 to 2013 for all three neighborhoods and for three antecedent moisture conditions.

Table 3.3: Change in runoff flows according to the three different categories of antecedent moisture conditions.

Antecedent moisture conditions	Dry (AMCI)	Average (AMCII)	Wet (AMCIII)
HELPMAN	1.5%	0.7%	0.3%
PROFESSORENBUURT	3.4%	1.5%	0.7%
SELWERD	2.2%	1.0%	0.4%

As expected, the change in runoff is largest with AMCI conditions. Also, the largest change is found in Professorenbuurt, since this neighborhood encountered the largest change in sealed area.

The calculated percentages are lower than results of the study by Perry and Nawaz (2008), which is according to expectation as the change of sealed area was also lower in the current study. To assess whether this change in runoff flow presents consequences to the neighborhood, the amount of runoff was compared with a simplified estimation of the sewer capacity in the neighborhood.

Table 3.4: Sewer capacity of the total area (J en L datamanagement, 2014).

	Capacity	Total area	Houses and roads	Threshold event
HELPMAN	190 m^3	243000 m^2	70450 m^2	2.7 mm
PROFESSORENBUURT	1028 m^3	201000 m^2	125510 m^2	8.2 mm
SELWERD	3685 m^3	506000 m^2	344756 m^2	10.7 mm

Table 3.4 shows the storage capacity of the sewer system in the neighborhoods. The storage capacity was determined as the volume of the sewer system at the overflow threshold; more water towards the sewers would lead to an overflow. The threshold takes into account 0.7 mm/h drainage by the sewers.

By dividing the sewer capacity by the sealed area that drains on the sewers, the maximum amount of rainfall before overflows occur can be determined. In the table, this threshold level is given when only roads and housing in the neighborhood are draining on the sewer system.

If the sealed areas in gardens in 2013 are incorporated in this calculation, the threshold of Helpman, Professorenbuurt and Selwerd are respectively 1.6 mm, 6.0 mm and 8.7 mm. As can be seen in figure 3.4, events of 10 mm/h occur on average just more than once a year. The threshold of Professorenbuurt is reached 10 times per year and the threshold of Helpman more frequent.

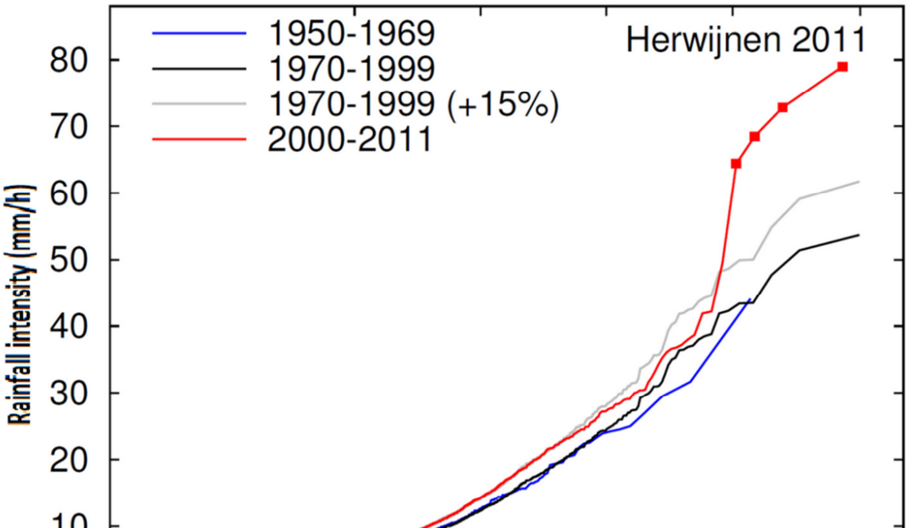

Figure 3.4: Rainfall intensity plotted against the frequency of the events (KNMI, 2014: http://www.knmi.nl/cms/viewimage.jsp?number=101716) .

The actual situation in Groningen does not experience overflows at this high frequency, which has several causes. Firstly, not all sealed areas drain on the sewer system. In general, 5 to 10% of the area drains on local water bodies if present. Also, fragmented sealed areas can drain on unpaved areas until the unpaved soil is saturated or the limits of infiltration speed are reached.
However, the threshold of Helpman is lower than accounted for by the reasons mentioned. Runoff from roads alone would cause overflows in Helpman multiple times per year, which is currently not the case (J en L datamanagement).
As reported in paragraph 2.2, Helpman lies on a branch of the Hondsrug. The slope in Helpman causes the rainwater to drain on downslope areas. As Helpman lies at the border of Groningen, the water is able to leave towards meadows and pastures outside Groningen. The increase of soil sealing by gardens is not expected to cause a higher overflow frequency or other water issues.
Selwerd and Professorenbuurt perceive different circumstances. Especially Professorenbuurt is densely built and lies near the center of the city. Rainwater has little means to leave the area and overflows occur frequently. Increased paving is expected to increase the frequency and the intensity of the overflows. In general, soil sealing leads to more runoff, but local conditions determine to a large extent what the effect of soil sealing in the area is.

Discussion of the method

In Helpman, the lay-out of the neighborhoods causes much of the runoff to drain on unpaved areas and therefore the eventual runoff stream to enter the sewer system is expected to be smaller than calculated. In contrast, both Selwerd and Professorenbuurt exhibit pathways at the back of the houses. Runoff from the back gardens can therefore likely stream to the sewers, though the total impervious area is examined and not the directly connected areas (as explained in paragraph 3.1). In all neighborhoods the actual runoff flows are expected to be less than calculated, but since this is the case for both 1998 and 2013, it is assumed that the percentile change is rather accurate.
Estimation of runoff from roads and houses to the sewers leads in Helpman to unexpected high volumes compared to the sewer capacity. This implies that, though generated runoff from gardens is estimated higher than realistic, other local factors cause biased results as well. The currently used method is only able to give a general indication of the increase of runoff, but the method does not suffice to estimate the relevance of the increase of runoff. Perry and Nawaz (2008) deemed their results significant, since the studied neighborhood experienced a higher frequency of overflows over time. According to J en L Datamanagement, no significant increase of overflows in the studied neighborhoods in Groningen was experienced. However, J en L datamanagement also emphasizes that rainfall is not uniform throughout the city and accurate measurements are lacking. As the frequency of overflows depends on both the amount of rainfall and the extent of sealing, it is therefore difficult to test the relevance and reliability of the current results. It is therefore recommendable to measure runoff flows and rainfall over multiple years to retrieve insight in the local effects on runoff generation.

Key findings

Runoff generation during a 19.5 mm event was calculated for the sealed situation in 1998 and 2013 in the three case-study areas. The change of the runoff flow was between 0.3 and 3.4%. Tests with the model showed a variance of the outcome according to soil type, antecedent moisture conditions and amount of rainfall. However, when these parameters are similar to all neighborhoods, Professorenbuurt shows the largest change in runoff generation. As Professorenbuurt also has the largest percentage of sealed area in 2013, the absolute amount of runoff per unit area is expected to be largest in this neighborhood.
Estimation of the effect of runoff to the sewer system show unexpected results, since Helpman would perceive frequent overflows due to small sewer capacity. The slope of the neighborhood causes most of the runoff to drain on lower situated areas, which is why Helpman does not en-

counter overflows every month. Apparently, local factors play a large role considering the consequence of runoff on sewer systems.

4. The Urban Heat Island

Generally, the temperature in urban areas is higher compared to its surrounding rural areas. This phenomenon is known as urban heating or the Urban Heat Island (UHI) effect (Wolters *et al.*, 2011). The UHI effect is most pronounced at late afternoon and night, whilst in the morning the effect can be negative (Oke, 1991).

UHI is caused by changes in radiative and thermal properties of the surfaces and structures within the urban area as well as the geometry of the city (Van Hove et al, 2011). The net effect of UHI intensities is variable among different locations. In a cold climate, the UHI can be perceived as beneficial as less energy is needed to heat the interior buildings and thermal comfort rises in these circumstances (Watkins *et al.,* 2007). This also holds true for winter seasons in temperate climates.

However, during the summer season in warm and temperate climates, the net effect results in reduced thermal comfort, premature deaths, reduced air quality and increased energy use due to air-conditioning within buildings (Watkins *et al.,* 2007)

The multiple facets of UHI result in studies throughout different disciplines. Architects (Ali-Toudert, 2005), urban planners (Sailor, 2008), meteorologists (Oke, 1991) and health institutions (GGD, 2013) are all engaged in the study of the UHI. The interest of planners and architects lies in the city design and building design. The street design can have a profound influence on the UHI and thermal comfort. Also, the energy requirements for air conditioning of a building depend on the UHI. Architects and designers therefore try to understand and calculate the effects of their designs.

In meteorology, apart from interest in the UHI itself, there is a large field of research investigating the influence of UHIs on downwind regions and the global climate (Bohnenstengel *et al.*, 2011). Multiple papers report sea-breezes caused by the urban areas (Bohnenstengel *et al.,* 2011; Masson, 2006).

Health institutions are mostly concerned with the relation of the UHI with thermal comfort (GGD, 2013). Mitigating measures to avoid premature deaths and heat-stress rely on profound knowledge of the UHI and its causes.

4.1 UHI processes

According to Oke (1991), several processes or characteristics can be recognized to contribute or influence the UHI. First of all, the urban geometry affects the local climate in two-fold: the outgoing long-wave radiation decreases in street canyons due to building and skyline influences. This process is often expressed and explained by the sky view factor (SVF); the fraction of the sky which is visible from the Earth's surface. The higher the buildings and other vertical surfaces become and the closer proximity these surfaces are, the lower the SVF will be. Low SVF values cause reflection and absorption of the long wave radiation emitted by the urban surfaces, reducing the net-outgoing long wave radiation (Wolters *et al.*, 2011).

As a low SVF exhibits multiple reflections causing a decrease of the effective albedo, the net incoming short-wave radiation is increased (Oke, 1991). The surfaces and buildings warm-up to a larger extent than rural surfaces (Wolters *et al.*, 2011). Counterwise, a low SVF can cause shading effects during periods of the day when the sun is at its lowest. In this case, the urban areas can be colder than the rural areas, resulting in a negative UHI effect.

Additionally, the urban building materials are characterized by thermal properties in favor of sensible heat storage, compared to undeveloped land. Also, heat release from people, animals and from the combustion of fuels, generally referred to as 'anthropogenic heat', add up to an increased temperature.

Oke (1991) refers to the urban greenhouse as a contributor to the UHI. The more polluted and warm urban atmosphere increases the net incoming long-wave radiation, which leads to direct warming of the urban area.

The reduction of evaporating sources reduces the latent heat and increases sensible heat. Evaporating sources can be water bodies as well as vegetation and bare soil. Vegetation and bare soil are scarcer in urban areas and sealed urban surfaces drain rapidly to the sewer system, reducing the water available for evaporation (Wolters *et al.*, 2011).

Finally, the urban areas provide shelter which reduces wind speed and flux and therefore the turbulent transfer of heat from within streets (Oke, 1991).

The UHI effect is influenced by multiple factors, all contributing accordingly to local conditions. Johnson *et al.* (1991) have studied the UHI mechanism by inserting hypothesized causes of the UHI into a model validated by field data. He found that except in extreme climates, the street geometry and thermal storage of building materials are the dominant factors to cause UHI. However, in most European cities and suburbs street geometry is not expected to be the most important factor (Whitford, 2000).

Johnson *et al.* (1991) show that the urban greenhouse effect has a relatively minor influence. Cloud cover reduces the UHI, since it reduces the intensity of short-wave radiation which warms urban areas more than rural areas. Similarly, fog in the rural area can enhance the UHI (Steeneveld *et al.*, 2011).

The anthropogenic heat flux is considered a minor influence. However, large Japanese cities are examples of exceptions. The high population density and high energy consumption cause the anthropogenic flux to explain the areas of maximum UHI (Masson, 2006). Also in cold weather or cold climates, the anthropogenic heat source can be a dominant factor due to intense heating practices within buildings. However, wall insulation is improving over the years, mitigating this effect.

UHI patterns and intensities

The intensity of the UHI is location dependent, due to the spatial variability of UHI influencing factors. Some of these factors also comprise temporal variability, causing the UHI to vary on a seasonal and a daily basis.

A study of Wilby (2003) shows that the hourly variation of the intensity varies along different sites (figure 4.1).

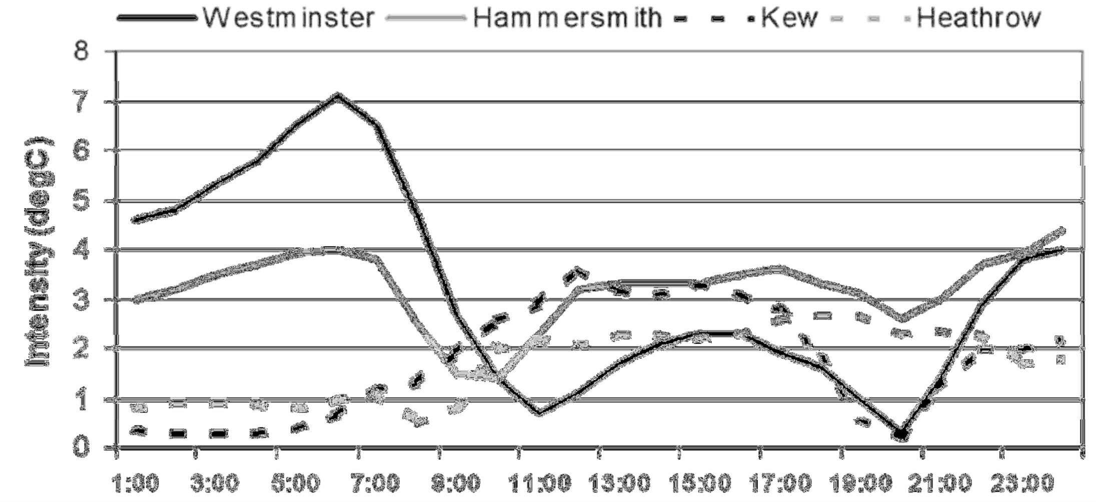

Figure 4.1: Hourly variation in UHI intensity at selected sites with respect to the reference station at Bracknell, during six days in July and August, 1999 and 2000 (Wilby, 2003).

The reported UHI intensities by Wilby are measurements at the selected sites with respect to the reference station Bracknell. The distances from central London are 2 km (Westminster), 6 km (Hammersmith), 13 km (Kew) and 26 km (Heathrow). The two sites closest to the city center show a peak nocturnal UHI at 7:00 h, whilst the less urbanized sites show larger UHI intensities during day-time.

Therefore, Wilby (2003) concludes that temporal and spatial variations in UHI intensity are closely related to the extent of urbanization. Extensive urbanization modifies the radiation and energy balance of the Earth's surface (Wilby, 2003).

In general, the UHI is mostly favored by locally driven meteorological conditions, that is: less mixing of the warm urban air with rural air favors a large temperature difference between both locations (Oke, 1991). The relations between UHI and weather conditions described by Arnfield (2003) complement this statement. According to Arnfield, increasing wind speeds and cloud cover cause a decreasing UHI intensity. Secondly, the UHI is most pronounced during summer and UHI generally increases with increasing city size and population. Finally, the UHI is most pronounced at night. During night short-wave radiation is absent causing the rural areas to cool down rapidly. The urban areas, however, cool down less, because the buildings materials gradually emit long-wave radiation stored during the day. Therefore, the UHI reaches its maximum intensity several hours after sunset (Johnson 1991). Shortly after sunrise, occasionally a negative UHI can be measured. The city geometry causes large shadowy areas which remain cool through the morning, while the rural areas warm up due to the short-wave radiation.

Wolters (2011) found similar relations. The UHI increased with population density, after sunset and during summer. In one dwelling, the temperature was measured on the roof and in the garden. The UHI effect only differed in the early morning. In these circumstances, the UHI was largest on the roof, according to the authors due to shadow-effects in the garden.

Other studies have contradicted the statements of Arnfield (2003) and Wolters (2010), due to variety in urban geometry and climate (Whitford, 2000).

Since the UHI fluctuates through time and space, the mean annual or daily UHI values of a site is not able to provide information on extreme situations. It is the extreme situation which is most relevant with regard to negatively perceived effects of the UHI; Heat stress is more likely to occur during a heat wave compared to an 'average' summer day. On the contrary, averaged UHI values can be of importance to the impact of the urban climate on e.g. organisms and macro climate.

To assess extreme situations, a special feature called the maximum UHI is often used. The maximum UHI is the measured or calculated difference between rural and urban temperatures under the circumstances most favorable for a large value. For instance, a cloudless sky, low wind speeds and several hours after sunset are conditions generally used in temperate climates.

The UHI_{max} is estimated by Oke (1991) between 3 and 10 K. Wilby (2003) reports a maximum nocturnal UHI of 7 K in London city center. Wolters (2011) reports a maximum UHI around 5 and 6 K in Dutch cities.

The UHI effect can be studied on a local scale at the pedestrian level as well as on top of buildings and above. The smallest scale is the micro-scale in which the influence of individual objects – e.g. a wall, a small pond - plays a role (Oke, 2006). The local scale covers a neighborhood. In contrast, the meso-scale covers the urban area; the influence of the processes is averaged to a single urban heat island which influences the meso climate (figure 4.2).

Complementary to the scale of the study, the urban atmosphere is generally divided in two layers: The urban canopy layer (UCL), which is the layer between the soil and the average roof height; and the urban boundary layer (UBL) which is the layer between rooftops and the interference with the atmosphere (Oke, 2006).

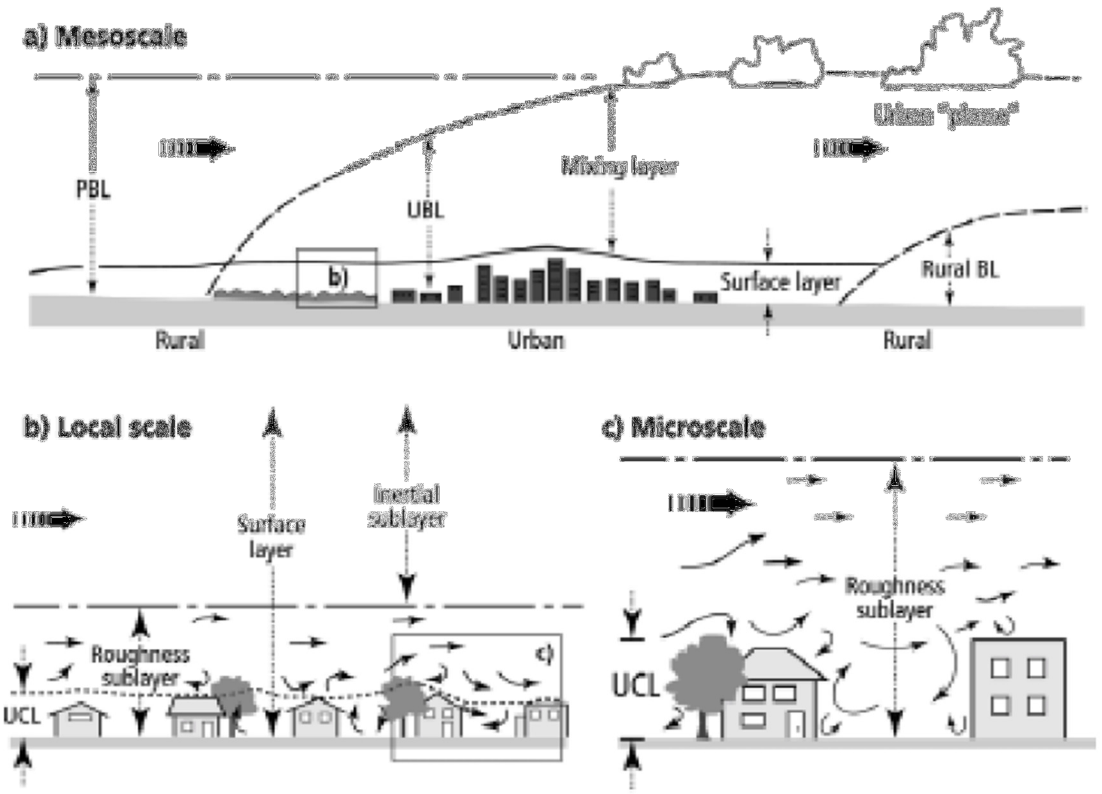

Figure 4.2: Schematic depiction of meso-, local-, and micro scale climate (Oke, 1991).

Implications for modeling

It is evident that soil sealing is not the only factor influencing the urban climate. The processes causing the UHI are numerous and possibly interdependent. It will therefore be difficult to express the UHI as a function of sealed surface in a general manner. Instead, a model incorporating several (or all) processes involved will be needed to estimate the UHI and compare situations with a different extent of sealing in a specific location.

Regarding UHI consequences, the focus of policy and society is generally on the increasing premature deaths and heat stress. Therefore, this study will focus on determining the UHI during circumstances in favor of a high UHI value, modelling a 24 hour cycle to determine the time of the maximum value.

In line with the focus on heat stress, the UHI will be calculated on a local scale. The effect of individual objects can be studied, e.g. small patches of pavement, and the effect of soil sealing on the average temperature in a neighborhood. The meso-scale impact or the macro climate is a problem of different proportion and will not be studied in this research.

According to Montavez *et al.*, (2000) it is important to distinguish between surface and air temperatures. Temperatures of surfaces and air show different values and trends, since advection and convection processes influence the air more than the surfaces. With regard to heat-stress and thermal comfort, air temperature is the desired output of the model.

4.2 UHI models

The number of models with the sole purpose to calculate the UHI, mentioned in literature, is limited. However, the more general meteorological and air quality models are more numerous and these models are quite often also able to predict or calculate the UHI. The models range from

single equations to calculate the urban surface or air temperature to models that incorporate e.g. deep soil temperature, humidity and wind speed simulation.
As with climate scales, models can be divided in methods to simulate climate in the urban canopy layer and methods to simulate climate in the urban boundary layer. Furthermore, the functionality or the objectives of the models differ: e.g. emergency preparedness models, atmospheric pollution models or urban or regional climate models (Baklanov *et al.*, 2009). Generally, models meant to study the effect of cities on the macro climate can be integrated with macro climate models or weather models. Though these models do not match with the objective of this study, several of these models are able to simulate the micro and local scale and could be applied to this study. Therefore, several macro-climate oriented models will be incorporated in the model evaluation. Furthermore, regression models are available (Steeneveld *et al.*, 2011) as well as advanced numerical models.

Model evaluation

Table 4.1 lists the evaluated models. The table gives the model names, the general objective of the model, the most important input parameters, the generated output and the reference of a case-study in which the model was used.

Table 4.1: Description of different climate models.

Model	Objective	Input	Output	Case studies
Levermore and Cheung	To calculate the maximum UHI effect in urban canyon	Spatial properties of slabs, conductivity, cloud cover, soil temperature and interior building temperature	UHI max during nighttime	Levermore and Cheung, 2012
Montavez	To calculate the UHI in urban canyons and study the mechanism	Initial temperature, thermal admittance, H/W-ratio, emissivity, incoming long-wave radiation	Urban and rural temperatures during night-time conditions	Montavez, 2000
ENVI-met 3.1	To simulate the urban micro climate	Initial temperature, initial humidity, relative humidity, rough-ness coefficient	Air temperature, soil temperature, wind vectors, humidity	Ali-Toudert, 2005
SHIM	Calculate urban and rural surface temperatures in nighttime condition	Initial surface, deep soil and building temperatures; thermal admittance, SVF, emissivity, incoming long-wave radiation	Soil and surface temperature during nighttime conditions	Johnson *et al.*, 1991; Oke *et al.*, 1991.
Tso *et al.*	Urban canyon model to calculate urban surface and soil temperatures	Specific heat and density of the soil, soil thermal conductivity, specific heat and average mass of concrete, roughness length, height UBL, wind speed and temperature at UBL, evaporation fraction.	Soil and surface temperature during nighttime conditions	Tso *et al.*, 1991; Whitford *et al.*, 2001
MORUSES	Predict city air temperatures and provide input to weather models	Emissivity and albedo of urban materials, roughness length, thermal conductivity, thermal heat capacity.	Air temperatures and Energy balance fluxes	Bohnenstengel *et al.*, 2011.
Steeneveld *et al.*	UHI as a function of vegetation	A percentage of vegetation in the study area	Mean and 95 percentile UHI in Dutch cities	Steeneveld *et al.*, 2011

Table 4.2 compares the different models according to their availability and objective. It shows whether different surface characteristics can be inserted in the model, whether air temperature is calculated and if the model presents an urban canyon. More elaborate descriptions of the models can be found in Appendix C.

Table 4.2: Comparison of different climate models.

Model	Available	Fits objective	Input different surfaces possible	Air temperature	Urban canyon
Levermore and Cheung	▨	▨	After adjustments		▨
Montavez	▨	▨			▨
ENVI-met 3.1	▨	▨	▨	▨	
SHIM	▨	▨			▨
Tso *et al.*		▨	After adjustments		▨
MORUSES		▨	▨	▨	
Steeneveld *et al.*	▨	▨		▨	

The limited availability of UHI measurements in Groningen excludes the use of empirical models and thus of the model by Steeneveld *et al.,* (2011).

To consider the applicability of a model for this study, the objective, the level of complexity and the input and output data should match with the study's objective and available data and desired computational power.

Models incorporate vegetation with differing degrees. In this research, the degree of soil sealing will be measured, so no data of the vegetation is recovered. Differentiation in different types of vegetation is therefore less important to this study. Similarly to vegetation, anthropogenic fluxes are not measured in this research so the model does not need to incorporate calculations of these fluxes.

Modelling of the urban morphology is more important in this study, since the neighborhoods are generally not represented by an urban canyon, excluding the most simple approaches. Also, it has to be possible to define the characteristics of buildings, paving and roads separately. Additionally, the different orientations (of the street e.g. from north to south or from east to west) of the surfaces can be incorporated in the model. This is necessary especially in case temporal variations are modelled, since shading effects and reflections will vary widely during the timeframe of the simulation.

As with morphology approaches, the assumed number of reflections is especially crucial in cases with long and high buildings. Albedo and emissivity are relevant in this research, as these vary with regard to sealed soil and bare soil.

Finally the storage heat flux is important as it is one of the key elements of sealed surface that contributes to the UHI. ENVI-Met is the only model which is available online, does not represent an urban canyon and calculates the air temperature. The one disadvantage is that the model does not include heat storage in buildings. However, all other models that include heat storage fluxes calculate surface temperatures. With regard to heat-stress, air temperature simulations are more relevant and accurate, thus ENVI-Met will be used in this study.

4.3 Modelling results

To explore the behavior of the model concerning the input parameters, several simulations were performed with different input parameters. All output consisted of the air temperature at 1.60 m above surface level in a period of 24 h, from 6:00 h to 6:00 h the next day.

First, simulations of a grass area and a paved area were compared to test the effect of paving in the model. As input of the model, both simulations start at 293 K after which immediately the temperature of paving is higher and remains higher than the grass area throughout the 24 hours period of simulation. The maximum temperature difference is 0.7 - 0.8 K and occurs at 16:00 h (figure 4.3). The temperature difference drops during the night and is at its minimum of 0.30 K at 6:00 h at the end of the simulation. The higher temperatures of the paved area can be explained by a lack of water for evaporation; evaporation cools the grass area. Also, the paved areas have a different albedo compared to the grass area. A higher temperature difference was expected after sunset, since the paved areas will release heat while the grass area cools down rapidly after sunset.

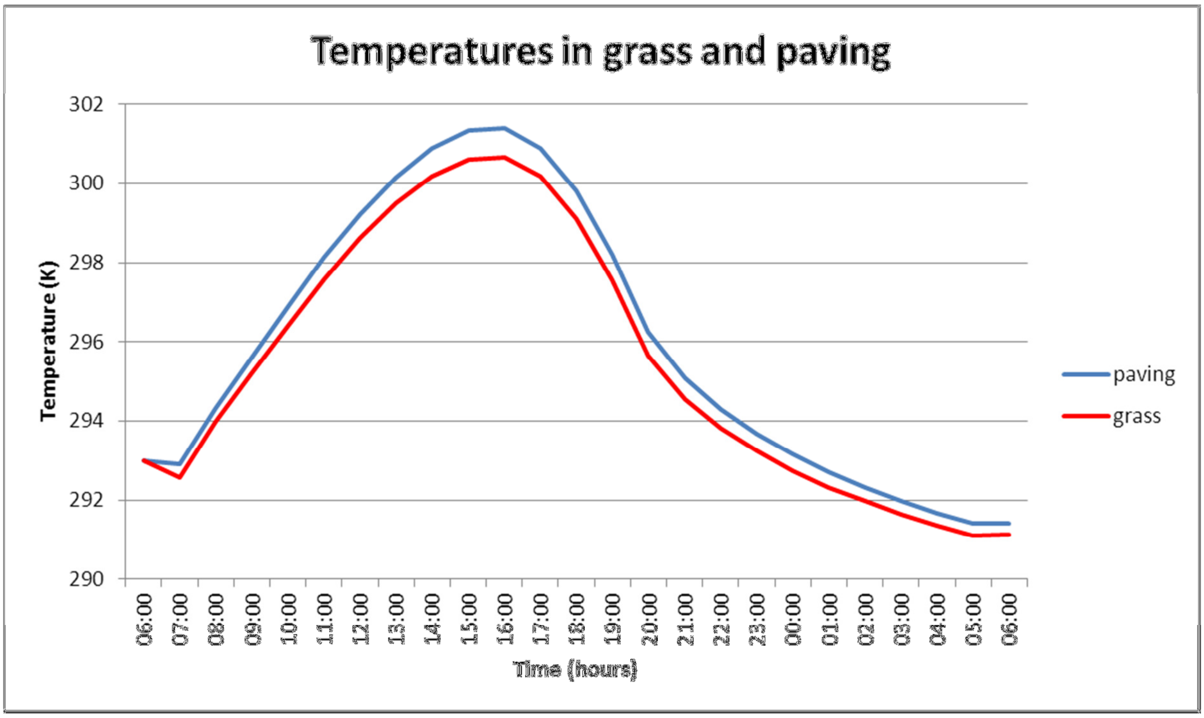

Figure 4.3: Simulated temperatures of grass and paved areas.

Secondly, a building of 8 meters high and 8 meters wide was introduced in the simulation. The building stretched the complete length of the simulated areas and was oriented from north to south. In one simulation, the eastern area next to the building was grass and the western area was paved and vice versa in the second simulation. The average temperatures of both simulations were similar to the temperatures of the grass area. Figure 4.4 shows average temperatures of the grass and paving areas individually. The areas at the east side of the building show similar temperatures and trends compared to figure 4.3: the paved area shows higher temperature throughout the 24 hour simulation and the maximum difference is at 16:00 h. However, the areas west of the building show significantly lower temperatures during the day than the areas east of the building. The western areas are shaded during the warmest period of the day, which causes maximum temperature differences of respectively 1.0 and 1.7 K. In the afternoon, the eastern areas are shaded and cool down faster than the western areas, resulting in lower temperatures during the night.

The paved area and the grass area west of the building show similar temperatures. The similarity at night is unexpected and confirms suspicions that the model does not include heat storage of the paved areas, a feature that would cause a temperature difference during the night between grass and paved areas. Also, the albedos of grass and paving are similar or have marginal influence on the temperature.

On the other hand, the results imply that shading effects, by buildings or trees, are able to mitigate the increased temperature by soil sealing quite efficiently. However, the results of both figure 4.3 and 4.4 shows that the model lacks not only heat storage in buildings, but also heat storage in pavement. It is therefore difficult to estimate the effect of soil sealing and thus the effect of shading during a certain moment of the day.

As no heat storage in buildings is incorporated, it is expected that higher buildings cause more shade and cause lower temperatures. A simulation incorporating a building of 5 meters compared to the simulation with a building of 8 meters showed indeed a higher average temperature by 0.2 K at 15:00 h. The cooling effect of buildings is debatable, since buildings store heat and release this energy during the night, a feature not incorporated in the model. Also, the buildings might reduce wind speeds which favor higher temperatures.

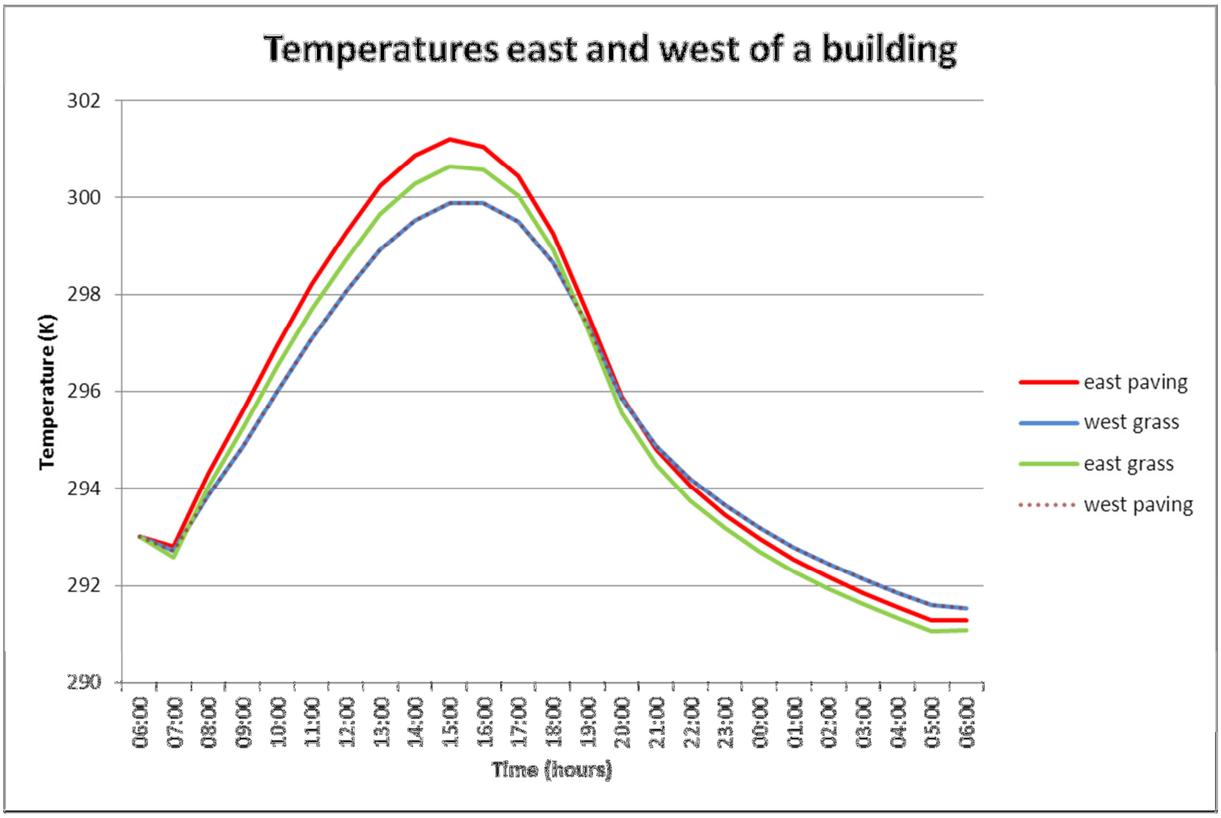

Figure 4.4: Simulated temperatures of paving and grass, east and west of a 8 meter high building.

Other parameters influencing the temperatures are e.g. initial wind speed. Higher wind speeds cause lower temperatures and temperature differences. Also, the orientation of buildings affects the average temperature of the simulated area. In addition, the size of the simulated area affects the average temperature due to boundary effects of the model. Therefore, it is not sensible to compare the different neighborhoods with each other, as they have different sizes.

Comparing all simulations, it is evident that paving alone results in the highest temperatures. This seems logical since the other simulations include at least a patch of grass, which should have an effect on the average temperature. However, the grass simulation does not have the lowest temperatures at all times. Shading effects cause the simulations with a building to have slightly lower temperatures. The end temperatures of building simulations are higher, so cooling was less rapid than in the grass simulation.

Case-study results and discussion

To determine possible temperature differences between 1998 and 2013, simulations of small areas of the neighborhood were performed. The houses, sealed area and unpaved areas were drawn in the model to simulate the sample of the neighborhood.

Figure 4.5 shows the temperatures of Selwerd in 1998 and 2013. Also, a scenario with the total garden area paved and a scenario with only grass area are shown. The average temperatures of 1998 and 2013 are similar throughout the simulation. Also, the simulation of a grass garden shows similar temperatures. The paved garden scenario shows elevated temperatures, showing its maximum of 0.3 K between 14:00 h and 15:00 h.

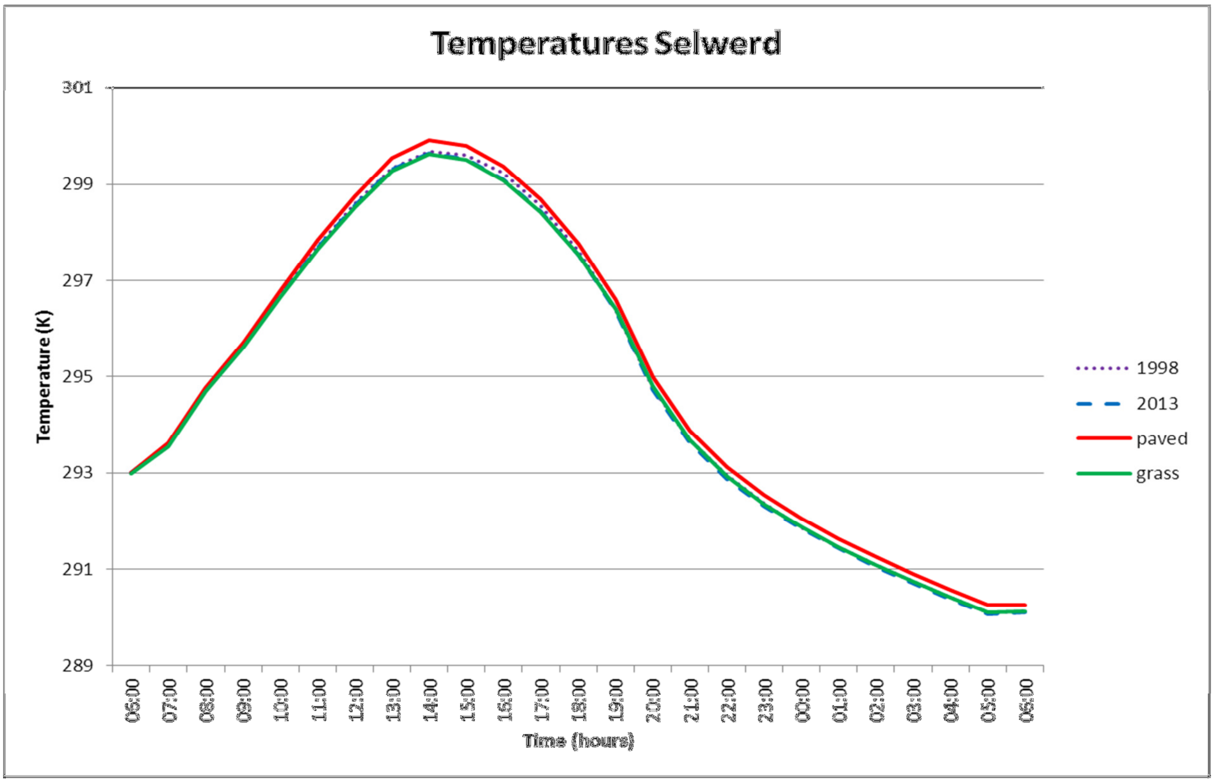

Figure 4.5: Temperatures in Selwerd in 1998, 2013 and scenarios with 100% grass gardens and 100% paved gardens.

The small difference between the years 1998 and 2013 was expected, since the change in the simulated area is marginal. The difference between the paved scenario and the grass scenario is smaller compared to simulations in paragraph 4.3.1, which is due to the large area of the houses. The houses cause the changeable area to be smaller and the houses cause shades, minimizing the effect of soil sealing. As explained in the previous paragraph, the exclusion of heat storage in the model causes lower simulated night temperatures than expected.

Figures 4.6 and 4.7 show the simulated temperatures in respectively Helpman and Professorenbuurt. The results are similar to the results in Selwerd; the temperatures of 1998 and 2013 are similar. The temperatures in the grass scenario are slightly less, but the largest temperature difference can be found in the paved scenario. The maximum difference between paved and grass scenario are 0.2 K in Professorenbuurt and 0.7 K in Helpman.

According to the simulations, Helpman can experience the largest temperature rise when gardens are completely sealed. Since Helpman is the least densely built of all neighborhoods and is therefore the most similar to the first simulation: comparison of a grass area with a paved area.

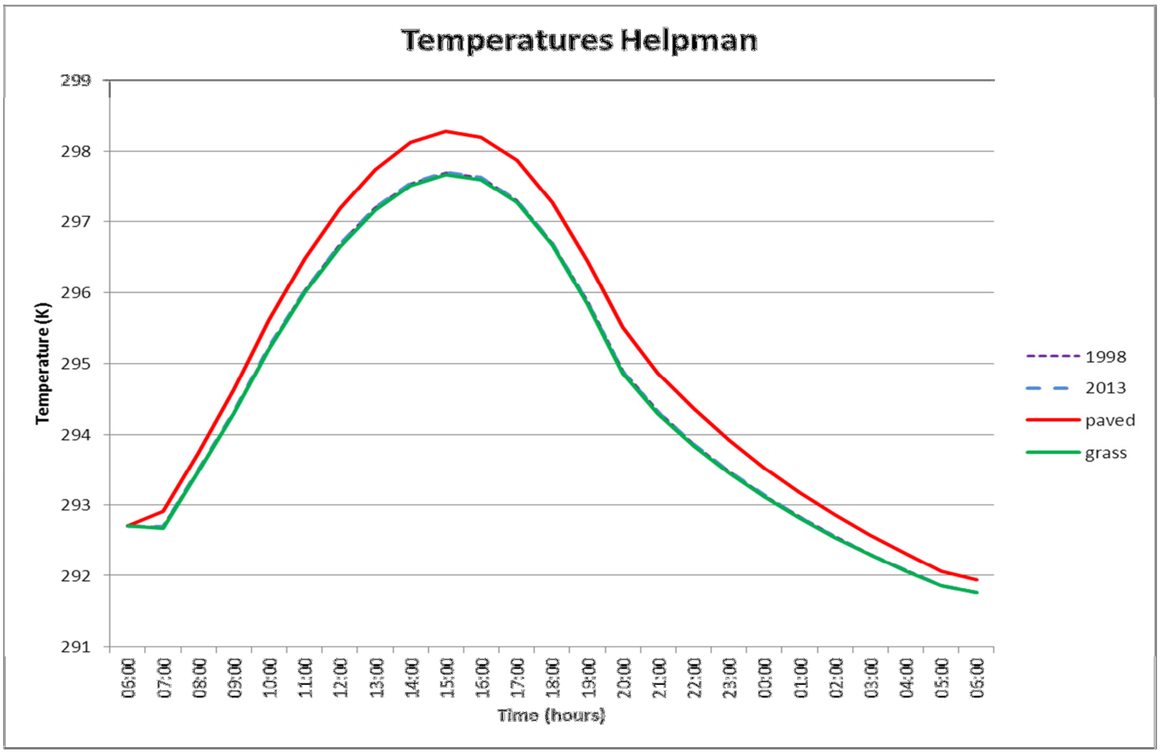

Figure 4.6: Temperature in Helpman in 1998, 2013 and scenarios with 100% grass gardens and 100% paved gardens.

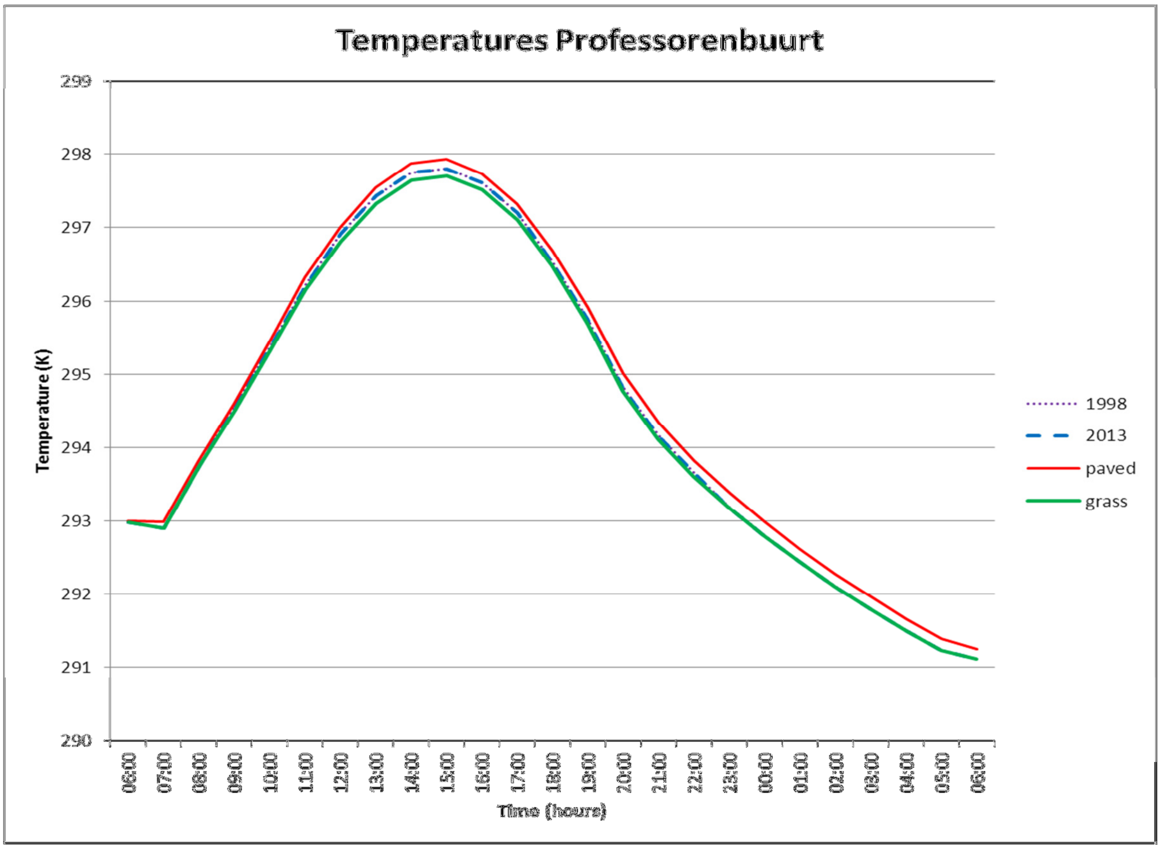

Figure 4.7: Temperatures in Professorenbuurt in 1998, 2013 and scenarios with 100% grass gardens and 100% paved gardens.

To results can be compared to studies relating air temperature with increased death rates to assess their relevance.

The CBS (Central agency of Statistics, 2010) shows an increase of deaths related to increased temperatures. According to the calculations by the CBS (2010), per degree temperature rise above the long-term average temperature leads to 30 deaths per week in the Netherlands. As the population in the Netherlands counted 16.8 million people in 2013 (CBS, 2013) and the population of Groningen 198 000 (Gemeente Groningen, 2014), on average the amount of deaths would increase by less than one person per week per degree temperature rise. The maximum difference of 0.7 K between sealed and non-sealed areas would account for still less deaths. Apparently, soil sealing in private gardens leads to a relatively small number of premature deaths.

In addition, the GGD states that most premature deaths during heat waves are mainly caused by elevated indoor temperatures. It would therefore be necessary to determine indoor temperature rise by soil sealing.

Also, premature deaths during heat waves result from overload of the heart and dehydration. These ailments are effected by multiple factors including temperature, wind and humidity. Apparently, the relation between temperature and premature deaths is not straightforward.

Discussion method

The ENVI-Met model was used, since it is able to model the microclimate on a small scale. It is one of the few models which calculates the air temperature without an urban canyon fundament. The model does not include heat storage, a main driver of elevated night temperatures caused by soil sealing. The models which include heat storage in materials generally aim to simulate surface temperatures. Another model would be needed to transform expected surface temperatures into air temperatures.

Ali-Toudert (2005) emphasizes the fact that ENVI-Met simulations of night temperatures are not accurate and day-time air temperatures are slightly underestimated. Comparison of simulations with field measurements showed deviations of 1 - 2 K (Ali-toudert, 2005). Comparing a possible deviation of the model of 1 -2 K to the simulated temperature difference of 0.7 - 0.8 K, the results seem insignificant. However, the current study does not aim to estimate absolute temperatures, which is the case in the study of Ali-Toudert. The present study simulates temperature differences and therefore the day-time results are regarded to be rather accurate, with the remark that the temperature differences are slightly underestimated during the day and to a larger extent underestimated during nighttime.

Key findings

The ENVI-Met model was used to estimate the air temperature difference between the sealed situation of 1998 and 2013 in the neighborhoods. Also, the model was used to run simulations of scenarios.

Simulation of scenarios showed that the model does not take into account the heat storage in buildings nor in paving. Therefore, night temperatures will be underestimated since heat storage gives rise to heat release at night, causing less cooling compared to unpaved or unsealed soils.

Also, the model showed a maximum difference of 0.7 - 0.8 K between a grass area and a paved area. The maximum value occurred at 16:00 h. Furthermore, shading by buildings caused large temperature drops, though it is debatable what the cumulative effect of a building would be if heat storage was included in the model. Finally, the orientation of the building influences results, as does the height of the building; higher buildings cause lower temperatures due to shading effects.

Temperature simulations in the neighborhoods showed marginal temperature differences between 1998 and 2013. However, temperature differences between a grass garden and a paved garden were more significant; respectively 0.7 K, 0.3 K and 0.2 K for Helpman, Selwerd and Professorenbuurt.

The simulated temperatures will have a minor effect concerning premature deaths. However, nighttime temperatures are underestimated, so it cannot be concluded that soil sealing has a minor effect on premature deaths as a results of this study.

Also, premature deaths and heat-stress are effected by multiple factors, while this study focused on the air temperatures.

Finally, the study did not investigate the relation between temperature rise and the effect on animal and plant life in the city. It is recommendable to investigate this relation in order to assess the relevance of temperature rise or ‘climate change’ by soil sealing.

5. Research Conclusion

In this research, the aim was to estimate the contribution of soil sealing in private gardens to runoff and urban heating. Mapping of gardens in Groningen showed a large difference between the neighborhoods in parcel size, relative garden area and relative sealed area. Helpman has the largest garden area, while Selwerd and Professorenbuurt show the largest trend concerning increased sealed area in the garden. Although the influence of gardens in Helpman to physical effects is largest (since the area is the largest), the increase or change of physical processes is expected most in Selwerd and Professorenbuurt. The relevance of the soil sealing trend depends on effects of runoff and UHI but also the future studies concerning the effect of soil sealing in gardens on biodiversity and air quality.

Simulations of runoff flows showed indeed the largest increase in Selwerd and Professorenbuurt. However, how these increased flows are experienced in the neighborhood is largely dependent on local factors. Simply comparing expected runoff flows with sewer capacities led to exaggerated results, as Helpman would experience overflows every month. Increased sealed area leads to more runoff, but the consequence and thus the relevance of soil sealing concerning water problems is less straightforward to predict. The current research was only able to give an indication of the increase of runoff flows, more detailed hydrologic simulations are needed to determine the change of frequency of overflows.

Simulations of temperatures of 1998 and 2013 showed similar results for all neighborhoods. No significant difference in average temperatures of 1998 and 2013 was found. Simulation of scenarios with completely paved gardens compared to grass gardens showed larger temperature differences. The nighttime temperature differences and to a lesser extent the day-time temperature differences are underestimated by the used model, due to exclusion of heat storage in buildings and pavement.
The effect of the temperature rise by soil sealing to premature deaths was calculated to be negligible. However, the health of people is influenced by multiple climate factors. Also, the GGD (p.c.) states that premature deaths are generally resulting from elevated indoor temperatures, complicating the questions whether soil sealing has a relevant impact on human health.

To conclude, this research showed that the urban garden takes up a large area of neighborhoods and that the gardens are sealed to a significant extent. Also, a trend towards more sealed area in the past 15 years was recognized. The contribution of soil sealing to runoff and urban heating could be quantified, but the relevance of the current results is difficult to assess not in the least because of questionable accuracy of especially the temperature simulations. A need for standards can be recognized, as results and relevance of soil sealing are sensitive to interpretation. How many deaths are needed to perceive soil sealing as a relevant causation? How much runoff is perceived as relevant?
However, the current study seems to imply that the physical effects of soil sealing in the case study areas in Groningen are minor. The current study results do not lead to general conclusions about soil sealing and its consequences, because of the dependence of the physical effects on local factors as well as the non-uniform occurrence of soil sealing.

5.1 Recommendations for future research

With regard to mapping the gardens, it is recommended to inspect property borders in advance of the mapping process. The trend could be oppressed by inclusion of non-private areas and exclusion of gardens managed by house-owners and renters.

To predict the effect of sealed gardens on runoff to the sewers, the analysis of paving in gardens can be extended by analyzing the extent of directly connected sealed areas. Also, gathering

gauged data of both runoff to sewers and rainfall can increase the accuracy of predictions. Local factors that influence the runoff flows or influence the severity of the consequences have to be taken into account.
Finally, the effect of soil sealing on water quality needs still to be assessed.

The currently used model for temperature simulations was not able to predict night temperatures accurately. It is recommended to design an air temperature model that includes heat storage or use a surface temperature model and find a means to convert the results to air temperatures.
Also, research is needed to look into the effect of elevated temperatures to animal and plant life.

Literature

Ali-Toudert, F., 2005. Dependence of outdoor thermal comfort on street design in hot and dry climate. Berichte des Meteorologischen Institutes der Universität Freiburg, Nr 15. Freiburg, November 2005.

Arnfield, A.J., 2003. Two decades of urban climate research: A review of turbulence, exchanges of energy and water, and the urban heat island. International Journal of Climatology 23, 1-26.

Baklanov, A., Grimmond, C.S.B., Mahura, A., Athanassiadou, A., 2009. Meteorological and Air quality models for urban areas. Springer.

Bhaduri, B., Harbor, J., Engel, B., Grove, M., 2000. Assessing Watershed-scale, long-term hydrologic impacts of land-use change using GIS-NPS model. Environmental Management 26 (6), 643-658.

Blaschke, T., 2010. Object based image analysis for remote sensing. ISPRS Journal of Photogrammetry and Remote Sensing 65, 2-16.

Bohnenstengel, S.I., Evans, S., Clark, P.A., Belcher, S.E., 2011. Simulations of the London urban heat island. Quarterly Journal of the Royal Meteorological Society 137, 1625-1640.

Brun, S.E., Band, L.E., 2000. Simulating runoff behavior in an urbanizing watershed. Computers, Environment and Urban Systems 24, 5–22.

CBS, 2010: http://www.cbs.nl/nl-NL/menu/themas/bevolking/publicaties/artikelen/archief/2010/2010-3172-wm.htm. Accessed March 2014.

CBS, 2013: http://www.cbs.nl/NR/rdonlyres/D8CB211C-1F22-4185-8873-28F2747A05BD/0/pb14n006.pdf. Accessed March 2014.

Chormanski, J., Van de Voorde, T., De Roeck, T., Batelaan, O., Canters, F., 2008. Improving distributed runoff prediction in urbanized catchments with remote sensing based estimates of impervious surface cover. Sensors 8 (2), 910–932.

Chow, V.T., Maidment, D.R., Mays, L.W., 1988. Applied hydrology. McGraw-Hill International Editions, Civil Engineering Series.

Conners, J.P., Galetti, C.S., Chow, W.T.L., 2013. Landscape configuration and urban heat island effects: assessing the relationship between landscape characteristics and land surface temperature in Phoenix, Arizona. Landscape Ecology 28, 271-281.

European Commission, March 2012. In-depth report: Soil Sealing. Retrieved from: http://ec.europa.eu/environment/integration/research/newsalert/indepth_reports.htm

Feldman, A.D. Hydrologic Modeling System HEC-HMS, Technical Reference Manual. US Army Corps of Engineers, March 2000.

Gemeente Groningen, 2014: http://gemeente.groningen.nl/statistiek/aantal-inwoners-groningen-loopt-op-tot-197.800. Accessed March 2014.

Haase, D. (2009). Effects of urbanisation on the water balance – A long-term trajectory. Environmental Impact Assessment Review. 29: 211-219.

Harbor, J.M., 1994. A Practical method for estimating the impact of land-use change on surface runoff, groundwater recharge and wetland hydrology. Journal of the American Planning Association, 95-108.

Heaney, J.P., Huber, W.C., Nix, S.J. Storm water management model level 1, Preliminary screening procedures. EPA-600/2-76-275, October 1976.

Huber, W., Dickinson, R., 1988. Storm Water Management Model User's Manual. US Environmental Protection Agency, Georgia.

Jacobson, C.R., 2011. Identification and quantification of the hydrological impacts of imperviousness in urban catchments: a review. Journal of Environmental Management 92, 1438-1448.

Johnson, G. T., Oke, T. R., Lyons, T. J., Steyn, D. G., Watson, 1. D., and Voogt, J. A.: 1991, 'Simulation of Surface Urban Heat Islands, Part 1: Theory and Tests against Field Data', Boundary-Layer Meteorology. 56, 275-294.

Kampouraki, M., Wood, G.A., Brewer, T.R., 2008. Opportunities and limitations of object-based image analysis for detecting urban impervious and vegetated surfaces using true-colour aerial photography. Object-Based Image Analysis, Lecture Notes in Geo-information and Cartography 2008, pp 555-569.

Kang, K., Merwade, V., 2011. Development and application of a storage-release based distributed hydrologic model using GIS. Journal of Hydrology 403, 1-13.

Klokk, E.J., 2012. Toelichting op de hittekaarten van Groningen. (Communication to the GGD Groningen, February 16th, 2012)

Levermore, G.J., Cheung Meng, H.K.W., 2012. A low-order canyon model to estimate the influence of canyon shape on the maximum urban heat island effect. Building Services Eng. Res. Technology 33 (4), 371-385.

Loram, A., Tratalos, J., Warren, P.H., Gaston, K.J., 2007. Urban domestic gardens: the extent & structure of the resource in five major cities. Landscape Ecology 22: 601-615.

Masson, V., 2006. Urban surface modeling and the meso-scale impact of cities. Theoretical and Applied Climatology 84, 35-45.

Mathieu. R., Freeman, C., Aryal, J., 2007. Mapping private gardens in urban areas using object-oriented techniques and very high-resolution satellite imagery. Landscape and Urban Planning 81: 179-192.

McDonald, A.G., Bealey, W.J., Fowler, D., Dragosits, U., Skiba, U., Smith, R.I., Donovan, R.G., Brett, H.E., Hewitt, C.N., Nemitz, E. 2007. Quantifying the effect of urban tree planting on concentrations and depositions of PM10 in two UK conurbations. Atmospheric Environment, 41(38): 8455-8467.

Melesse, A.M., Graham, W.D., 2004. Storm runoff prediction based on a spatially distributed travel time method utilizing remote sensing and GIS. Journal of the American Resources Association, No 02150,

Melesse, A.M., Shih, S.F., 2002. Spatially distributed storm runoff depth estimation using Landsat images and GIS. Computers and Electronics in Agriculture 37, 173-183.

Montavez, J., Jimenez, J., Sarsa, A., 2000. A Monte Carlo model of the nocturnal surface temperatures in urban canyons. Boundary-Layer Meteorology 96, 433-452.

Oke T, Johnson G, Steyn D, Watson I. 1991. Simulation of surface Urban heat island under 'Ideal' conditions. Part 2: diagnosis of causation. Boundary-Layer Meteorology 56: 339–358.

Oke, T.R., 2006. Initial guidance to obtain representative meteorological observations at urban sites. World Meteorological Organization, Instruments and observing methods, report no. 81 .

Pandit, A., Gopalakrishnan, G., 1996. Estimation of annual storm runoff coefficients by continuous simulation. Journal of Irrigation and Drainage Engineering 122 (4), 211–220.

Park, D., Jang, S., Roesner, L.A., 2012. Evaluation of multi-use stormwater detention basins for improved urban watershed management. Hydrological Processes 28, 1104-1113.

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: 1-13.

Prinsen, G., Hakvoort, H.A.M., Dahm, R., 2009. Neerslag-afvoermodellering met SOBEK-RR. Stromingen: vakblad voor hydrologen 15, 1-15.

Productschap tuinbouw, 2011, Tuinbeleving 2011 Een segmentatie van de Nederlandse tuinbezitter, Zoetermeer

Prokop, G., Jobstmann, H., Schönbauer, A., April 2011. Report on best practices for limiting soil sealing and mitigating its effects. Final Report European Commission.

Rijksinstituut voor volksgezondheid en milieu (RIVM). 2011. Het effect van vegetatie op de luchtkwaliteit. RIVM rapport 680705019

Sailor, D.J., 2008. A green roof model for building energy simulation programs. Energy and Buildings 40, 1466-1478.

Scalenghe, R., Marsan, F.A., 2008. The anthropogenic sealing of soils in urban areas. Landscape and Urban Planning 90 (2009), 1-10.

Steeneveld, G.J., Koopmans, S., Heusinkveld, B.G., van Hove, W.A., Holtslag, A.A.M., 2011. Quantifying urban heat island effects and human comfort for cities of variable size and urban morphology in the Netherlands. Journal of geophysical research 116, 1-14.

USDA, Technical Release 55. Urban Hydrology for Small Watersheds. National Resources Conservation Service, June 1986

Tso, C.P., Chan, B.K., Hashim, M.A., 1991. Analytical solutions to a near-neutral atmospheric surface energy balance with and without heat storage for urban climatological studies. American Meteorological Society 30, 413-424.

Van Hove, L.W.A., Steeneveld, G.J., Jacobs, C.M.J., Heusinkveld, B.G., Elbers, J.A., Moors, E.J., Holtslag, A.A.M., 2011. Exploring the Urban Heat Island Intensity of Dutch cities. Combined Wageningen University and Alterra report. Wageningen.

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: 57-66.

Watkins R, Palmer J, Kolokotroni M. Increased temperature and intensification of the urban heat island: Implications for human comfort and urban design. Built Environment 2007; 33: 85–96.

Whitford, V., Handley, J., Ennos, R., 2001. City form and natural process: indicators for the ecological performance of urban areas. Landscape Urban Plan. 57, 91–103.

Wilby RL. Past and projected trends in London's urban heat island. Weather 2003; 58: 251–60. (for comparison with my results of UHI and as an example of the great effect)

Wolters, D., Bessembinder, J., Brandsma, T., 2011. Inventarisatie urban heat island in Nederlandse steden met automatische waarnemingen door weeramateurs. Koninklijk Nederlands Meteorologisch Instituut, Ministerie van Infrastructuur en Milieu. De Bilt, 2011.

Zoppou. C., 1999. Review of Storm water models. CSIRO Land and Water, Canberra. Technical Report 52/99.

Personal communication:
Wout Veldstra, Municipal Ecologist.

GGD, Health Institute Groningen

J en L datamanagement,

Kadaster

Appendix A

Mapping in ArcGIS produces output as given in the table A. The area of the 6 specific categories in 2013 can be derived directly. Regarding the year 1998, more calculation is needed. The percentages in classes A - E represent the estimated extent of non-sealed or non-built area, 100% means no sealing in the selected polygon and 0% means a fully sealed polygon.

The values in the cells represent the area of the polygons in the particular classes. As every class represents a different percentage of unsealed surface, the values per class have to be converted to two values: sealed and non-sealed, in order to compare the situation of 2013 and 1998. For example, The value 4045 in class B represents an area of 4045 m^2 which showed an impervious area of 5-35% in 1998 in the polygons which were classified as Dwellings with attached sheds in 2013. To obtain clear figures on the total amount of sealed and non-sealed area, the number 4045 was multiplied by 0.2 (20%) and 0.8 (80%) to obtain respectively the non-sealed and sealed area in this cell; 20% is the average of 5 and 35%, which represents non-sealed soil, thus 80% present sealed soil. This method was applied to all classes and generated the total sealed and non-sealed area.

Table A: An example of the output of the mapping in ArcGIS by Kadaster

	Categories Area (m^2)	2013	A: 0 - 5%	B: 5 - 35%	C: 35 - 65%	D: 65 - 95%	E: 95 - 100%
1	**Dwellings with attached sheds**	31650	26467	4045	547	0	591
2	**Detached sheds**	4035	3348	161	53	0	474
3	**Paved area**	40866	18252	12590	6900	2144	980
4	**Unknown area**	0	0	0	0	0	0
5	**Unpaved area**	127078	0	288	509	25023	101259
6	**Small garden paths**	571	464	0	29	0	78
	TOTAL	**204200**	**48531**	**17083**	**8037**	**27167**	**103382**

Appendix B

Haase, 2009: ABIMO

The model is used to analyze the effect of land-use change on the long-term water balance. The objective is to raise the understanding of the impact of urbanization on urban hydrology. A test-case of Leipzig is used for a long-term trajectory of 130 years. The authors state that very few studies have studied the impact of urban growth from the beginning of industrialization on the natural environment. The case-study is meant to provide empirical evidence of the effect of urbanization on the urban water balance.

Parameters evapotranspiration, precipitation and water regulation are used to determine direct runoff and groundwater recharge rate. The model operates at the city level and assumes a certain percentage of imperviousness per land-use type. The authors argue that the outflow gauges of the city are not representative because the runoff is generated by a larger basin. Therefore, calculated runoff of the four time-steps are compared.

ABIMO uses the BAGROV-relation to calculate the so-called ‘actual evapotranspiration’, ET_a. The BAGROV relation describes the relation between precipitation and evaporation depending on drainage properties. The ABIMO model is adjusted for urban areas to estimate evaporation. In combination with an adapted runoff-model by Messer, direct runoff was calculated.

In Messer’s model, direct runoff is expressed as a function of the slope gradient, soil type, grain size, ground water level, land use and the degree of imperviousness; all summarized in the factor p. Direct runoff is equal to actual evapotranspiration abstracted from the total precipitation, multiplied by the factor p and divided by 100. Both the ABIMO model and Messer’s model are lumped.

The availability of ABIMO is not clear. No downloads seemed available on internet but also no purchase possibilities were recognized. Although multiple relations are stated in the literature, only a general table is given to show how p can be determined.

Kang and Merwade, 2011: STORE DHM

The model is called Storage Released based Distributed Hydrologic Model. It is a conceptual model for hydrologic simulations based on a storage-release approach. In this approach, each compartment (cell) can store water provided by neighboring cells. The water is then released to cells downstream of the initial cell. The release is based on the travel time, which can be calculated by a combination of the continuity and Manning’s equation. The model is to be used within GIS, since it is a distributed model.

The model was used to perform calculations on three case studies. However, first the model was calibrated against observed water flow from a single storm event.

Input data needed are topographic information (slope, flow direction), land cover data, soil data and rainfall data, either from rain gauges or radar.

The model calculates runoff, volumetric flow rate and travel time. Steady state uniform flow approximation and Manning’s equation are used to do the calculations. Runoff is calculated by the SCS curve number method. The flow rate and routing is calculated, using the storage release method. Each grid cell stores water to a certain accumulation and releases the water to its downstream neighboring cell. The storage in one cell is defined by the sum of the runoff term per time unit, the storage of previous time unit and the release of surrounding upstream cells minus the release of this cell during this time step. The release of water from a grid cell is dependent on the travel time. Travel time depends on overland flux and the surface flow rate, determined by Manning’s equation (incorporates the friction slope, the depth of water on the surface and the Manning’s roughness coefficient).

The model is calibrated by simulating a single storm event and comparing the results with measurements at a gauged station (USGS) at the outlet of each study site. Calibration is done manually, by modifying the Manning's roughness coefficient.

The method is used for watersheds and seems not to be aimed towards urban area estimations. Also, a very detailed grid with small cells will be needed to account for the impervious surfaces in gardens. Thus, detailed data of e.g. slope and flow direction would be needed to operate the model. This data is not available to this study.

SCS runoff curve number, TR55, 1986; Pandit and Gopalakrishnan, 1996

The model estimates how much of a rainfall event becomes runoff by means of the curve number method (Soil Conservation Service US). Data required for the method is land-use data, soil data, rainfall data and USDA, Technical Release 55 (TR55, 1986) to determine the curve numbers.

The land-use and the type of soil of the areas are needed to determine the curve number (CN). The CN values depend on soil type and land cover and can be found in TR55. Once the CN is found, runoff can be determined by a formula using the CN and annual precipitation. The calculations can be easily processed in an Excel worksheet. In this model, runoff is calculated as precipitation after initial abstraction by infiltration and interception by vegetation.

Pandit and Gopalakrishnan (1996) added variation of antecedent moisture conditions. The original model calculates runoff during average antecedent moisture conditions (AMCII). Pandit and Gopalakrichnan (1996) show relationships and equation to determine runoff after dry conditions (AMCI) and wet conditions (AMCIII). Prinsen (2009) emphasizes that the SCS method cannot be applied to long-term estimations of runoff.

The results from this model are percentages of change in runoff. The input required for the model is available and the model is applicable to urban areas. The model can be used as a first indications of runoff volumes and to study the effect of land-use change on urban hydrology (Pandit and Gopalakrishnan, 1996).

HSPF, Brun and Band, 2000

The model is a lumped catchment hydrologic model (hydrologic simulation program Fortran). The model is suitable for investigating the effect of land-use conversion on the hydrologic cycle, sediment and pollutant movement. The aim of the model is to provide a tool for decision-making processes with regard to watershed development. The model can be used to determine daily stream flow from the watershed and was designed to simulate multiple hydrologic and water quality processes. It can simulate pervious or impervious unit areas draining to a river or reservoir. Any time step and any study period can be simulated, implying that the model is suitable for both continuous and singe event simulation. Application of the model is meant primarily for non-urban catchments (Huber and Dickinson, 1988)

Required data depends on the desired simulation of the model. HSPF is able to simulate the watershed, snowmelt and water quality. Data records of daily precipitation and daily potential evapotranspiration are input data for watershed simulation. To estimate snowmelt, data of the air temperature, dew-point temperature, wind and solar radiation are required. Simulation of the water quality requires data of the air temperature, wind, solar radiation, humidity, cloud cover, point sources and pesticide applications. Finally parameters to describe the land area, channels and reservoirs are needed for all computations. Calibration with field data of either base-flow or runoff is necessary to obtain reliable results (Brun and Band, 2000).

The model was applied to a case study in Gwynns Falls, where the land-use was divided as agriculture, commercial, forest, open land, residential, barren and water. The storm flow (or runoff)

was measured at the gauging station downstream the study area. The storm flow divided by precipitation determines the runoff ratio. Over the years, no large increase in runoff ratio was observed. The trend could have been masked by the variable climate effects or the impervious cover was not significant enough to change the trend. Therefore, the authors conclude that observational studies should be complemented by modeling studies to investigate the system.
Output of the model in this case-study is the soil moisture storage and daily stream flow toward the gauging station.

Calibration was done by comparing computed results with gauged values. The computed values could be modified by changing ET parameters and interflow recession constants. The authors discuss that the model relies heavily on calibration and is therefore less suitable for predictions of scenarios. It is therefore less suitable to the current, also since the model is meant for large rural watersheds.

SWMM Level 1, Heaney et al. 1976

The SWMM Level 1 model was designed due to recognition of problems concerning the complexity of the original SWMM model. SWMM is too detailed for many users, therefore a simple screening model was developed to present a means to make rough estimations of runoff quantity and quality. The primary objective of the model is to estimate storm water pollution quantities, control alternatives and associated costs, though it is possible to only use the urban runoff modeling. The complete method also incorporates water use by industry, residents and other that influence water flow in sewer and drainage systems.

To operate the urban runoff model, one needs the mean annual precipitation, the percentage paved area and unpaved area. The runoff coefficient is computed as a function of percentage impervious area. The impervious area can be estimated by an empirical relation between population density and imperviousness. Also the depression storage can be estimated according to an empirical relation between depression storage and the percentage impervious area. By means of these simple equations one can calculate annual runoff. All the empirical relations are based on five US cities.

The model is the simplest of all evaluated models and only incorporated the share of impervious surface in its estimation of surface runoff.

SWMM (Storm Water Management Model, EPA), Huber and Dickinson

The model can be described as an urban runoff quantity and quality model. It simulates storm events, but is also able to compute continuous processes. The model requires meteorological inputs and watershed system characterization:

- Rainfall
- Catchment
- Conveyance
- Storage
- Treatment

The model consists of four ‘blocks’ which can operate independently. A runoff block to compute surface and sub-surface runoff, based on rainfall, antecedent conditions, land use and topography. The transport block can route flows and pollutants through the sewer and drainage systems. A storage block can compute the effects of control devices upon runoff flows and pollutants. Finally, a receiving block can optionally be connected to the SWMM framework.
According the authors it is essential that local data are available to verify or calibrate the model, though quantity predictions are often within error margins when accurate rainfall, area and imperviousness data are used. With regard to quality calculations, only relative effects on pollution may be studied if calibration is not possible. Also, the authors highlight that, if a simpler model can do the job, one should not use the more complex SWMM.

SDDH, Melesse and Graham, 2004

SDDH is a model to simulate storm water runoff, taking into account the spatial and temporal variability of runoff generation. The routing model is GIS integrated and based on travel time of the water. Overland travel time is computed by a combination of a steady state kinematic wave approximation and Manning's equation. The channel flow travel time was computed by means of the Manning's equation and the steady state continuity equation. A case study was performed in a river basin in the southeast of China. Eight storm runoff processes were simulated to calibrate and evaluate the approach.

The approach requires the study area to be covered by a grid. The individual cells need to be classified as either overland cells or channel cells (cells with a number of upstream cells, greater than a certain threshold). Classification can be done by means of GIS and the DEM (Digital Elevation Model). The DEM is also needed to determine the flow path and network. A flow direction function in GIS is able to determine for each cell the single downstream cell with the steepest descent. The model needs calibration, requiring the availability of storm runoff measurements.

In the case-study the approach is meant to predict the response of a catchment to storm runoff. To predict runoff production, the SCS-CN method was used (Chow et al., 1988). Runoff routing is performed by the SDDH approach. The approach is not specifically meant for urban catchments. In the case-study, 1.9% of the area was residential land-use. The total study area was 259 km^2. This implies that the model is not specifically suitable for the current study. To simulate routing, calibration is required for which the required data is not present. The estimation of runoff generation can be done by the SCS method as stand-alone.

SOBEK-RR

SOBEK is a computer program with a multitude of simulating possibilities, meant to calculate storage and flows in watersheds and drainage systems. SOBEK-RR is one segment of the SOBEK 'family'; RR is a deviation of rainfall-runoff. SOBEK-RR is the simplest of all modules and can be integrated with the more complex modules.

SOBEK-RR comprises several methods to calculate rainfall-runoff processes, from which the user can make a choice; the SCS method is one of the methods available. In addition, routing methods are in the program to calculate runoff flow to the canals and sewer system (Prinsen *et al.,* 2009).

SOBEK-RR can best be described as semi-distributed, though lumped calculations are possible. The model can be adjusted to apply to large watersheds or smaller areas. Though the model is capable of complex calculations, it is also fit to simulate simple runoff processes related to paved and unpaved areas. In the latter case, the method used is very similar to the original SCS-method.

It is possible in SOBEK-RR to simulate infiltration more accurately than the SCS method. However, this addition requires more intensive data of evaporation, the slope of the surface and infiltration capacity. There is a table with default parameters available (Module C2100, 1995), to make a first estimation, but without calibration data it is not possible to test the validity of these parameters in the specific case-study area of Groningen. Both continuous and events can be simulated.

Appendix C

Levermore and Cheung, 2012:

Levermore and Cheung present a simple mathematical model of an urban canyon. The model is used to determine the maximum UHI effect, by means of a simple algebraic equation. The method uses vertical and horizontal slabs to represent the city morphology. The rural area is presented by one single slab of length L, width W and thickness x. The urban canyon is presented by two vertical slabs and one horizontal slab (length, width, height and thickness). The urban energy balance is used to determine the temperature of the outer slab surface (at night, no wind, no clouds).

Input

The required input consists of the length, width, thickness, conductivity and height of the slab; cloud cover, the temperature of the soil and the interior building temperature

More input parameters are possible, because the model makes certain assumptions. For instance, the conductivity of the horizontal slab is similar to the vertical slabs, but the model could be adjusted to incorporate varying conductivities. This adjustment is essential to calculate canyons with different areas of sealed surface. Humidity and air pressure are not needed as an input.

Assumptions

- Only sensible heat transfer is considered, no vegetation or water is considered at the slab or the canyon.
- A constant Earth temperature is assumed, although the actual temperature fluctuates considerably during the day. Earth temperature (in Manchester) is 16.5°C.
- The conduction and turbulent heat transfer and advection terms are considered insignificant during night. It is assumed that the air above the slab surface is warmer than the slab surface itself because of radiation from the slab (so no convection term).
- The canyon receives the same solar irradiance as the slab because the opening of the canyon has the same area as the slab.
- Edge effects, where the vertical canyon sides join the slab are ignored.
- The density and specific heat capacity of the horizontal slab and the canyon are equal.
- Cloud cover is chosen zero, wind speed is zero, advection and convection are zero.
- It is assumed that the long wave losses are equal for both the horizontal slab and the canyon walls.

Levermore and Cheung (2012) have compared model results with field data. The UHI in Manchester was measured by subtracting the measured temperature of the rural station from the urban measurements. Measurements of 26 nights at 9 different point in Manchester city lead to a standard deviation of 1.12 K.

Montavez, 2000

This urban canyon model simulates thermal radiation, conductivity and convection by means of a Monte Carlo method. In a Monte Carlo method, the problem is stated as a probability density function. A computer can simulate all the probabilities by means of random numbers (Montavez, 2000).

A numerical model was formulated for the surface UHI in an urban canyon. The urban canyon represents an infinitely long street with connected buildings on both sides of the street. This configuration allows simplification of the equations, for instance because it simplifies determination of the SVF or H/W ratio and keeps this value constant.

The objective of the paper is to study the relative importance of different heat transfer mechanisms. The simulations are compared to observational results. Computation of the UHI is performed by simulating both the rural and the urban situation separately.

Input parameters are the initial temperature, thermal admittance, H/W-ratio, emissivity, the incoming long-wave radiation.

Assumptions

- The model only includes thermal radiation, conductivity and convection.
- The model is formulated for night-time conditions
- The surfaces are homogeneous and dry (to exclude latent heat)
- Clear skies and weak winds are assumed
- The canyon is infinitely long
- Walls and ground can only lose energy through their exterior surface
- There's no heat loss to outside the canyon through convection

Montavez (2000) provides equations and descriptions of how the model operates. However, no computer interface is available. Also, since the model assumes urban canyons, its applicability to cases in Groningen is limited. Especially villawijk Helpman is not best represented by urban canyon, considering the large gardens and spaces between the dwellings.

The paper of Montavez (2000) includes a comparison of the measured temperatures with calculated temperatures. Measurements of surface temperatures are generally performed by infrared images or thermometers. Observational data of 5 urban and rural cases are compared with the computations of both the Monte Carlo model and the outcomes of SHIM (Johnson *et al.,* 1991). It shows that the smallest correlation coefficient is 0.981. The maximum temperature difference is 1.4 K, while the smallest is 0.5 K. The comparison of SHIM with Monte Carlo method is only qualitatively given in a graph. In general, the Monte Carlo values correlate better with the observational values and it predicts the trend more accurately.

ENVI-Met

ENVI-met is a three dimensional microclimate model. It was designed as a tool for architects, environmental planners and urban climatologists. The input required for the model is limited, while a large number of outputs is generated. Input parameters are the urban morphology to be delivered in a drawing program, coordinates of the site and initial temperature. Possible outputs of the model are soil temperature, air temperature (at all spatial coordinates) and wind vectors,

Assumptions and settings

- The indoor temperature for buildings is constant through the simulation. It is not possible to adjust the temperature in buildings separately.
- The albedo and heat transmission of buildings cannot be defined separately for different buildings. Also, the program models flat roofs, since it is not capable of modelling inclined roof surfaces. Finally, heat storage in walls is not simulated.
- Though they can be introduced, the default settings account for cloud-free sky conditions.
- The model gives the possibility to insert emission sources of gases or particulate matter.
- The deep soil temperature is kept constant.
- Sealed soils automatically are accounted a soil humidity of zero.
- Envi-met models the incoming short wave radiation itself. The value of radiation can be adjusted by a factor (for the daily cycle).

Ali-Toudert, 2005 case study

This case study assessed the relation between street design and thermal comfort for pedestrians. The effect H/W ratios and different solar orientations on the micro climate are studied. Furthermore, specific architecture, e.g. galleries, horizontal overhangs and trees are studied with regard to their potential to enhance thermal comfort. Finally, the research focuses on local variations across the street, e.g. street center, street sides. Case-studies were performed in Ghardia,

Algeria and Freiburg, Germany. On-site measurements were compared to ENVI-met simulations of the sites.
The model was run multiple times to estimate the initial temperature. The height of 1.2 m above the ground was used as a representative of human comfort calculations.

SHIM, Johnson , 1991; Oke, 1991

This numerical model describes the cooling of rural and urban surfaces, using thermal and radiative characteristics of the surfaces as well as the geometry of the urban area. The urban area is represented by a street canyon.
The objective of the paper is to evaluate two numerical models. The output of the models is the surface temperature of rural and urban canyons, assuming cloudless skies, low wind speeds and night-time conditions. Under these simplified conditions, the otherwise complex numerical method can be reduced to a solvable analytic problem. The simpler model of SHIM (Surface Heat Island Model) uses a force-restore method, the more complicated version solves a system of partial differential equations.

The input for the model consists of initial surface temperatures, deep soil and building temperatures, surface thermal admittance, sky-view factor, surface emissivity and the incoming long-wave radiation to the total system. The input parameters can result from observational data or (empirical) equations.

Evaluation of the model is done by comparing the computations with observational data. The temperature data available are near-surface temperatures, opposed to the surface temperature calculations the model performs. The maximum deviation of calculated and observed values is 2 K. This deviation partly originates from the error of modelling the surface temperature while comparing this value with air temperature.

Tso et al., 1991

In this model, Tso *et al.,* (1991) applies simplifying assumptions to a numerical problem to obtain a relation which is analytically solvable. The authors refer to the energy balance as near-neutral, meaning that energy storage in buildings prevents the system to be in a steady-state situation.

In the model, it is assumed that all meteorological and soil parameters exhibit horizontal homogeneity. Anthropogenic heat sources are not taken into account and temperature, wind speed and humidity in the boundary layer are constant.
The model was validated with field data in a case study in Kuala Lumpur, Malaysia. The deviation of calculated surface temperatures with measured surface temperatures was between 0.04-2.2 K. However, the model calculates surface and soil temperatures, whereas the measured values are air temperatures, which are not the same (Levermore *et al.*, 2012)).
Input data for the model are specific heat of air, air density, soil specific heat, soil density, soil thermal conductivity, specific heat of concrete, latent heat evaporation of water, average mass of concrete, roughness length, height of the boundary layer, wind velocity at UBL, air temperature at UBL, specific humidity at UBL, Evaporation fraction at the surface, sky temperature, soil depth and the soil temperature at depth.

The output of the model is surface and soil temperatures under specific circumstances and with certain assumptions. The model requires multiple input parameters.
Applicability of the model to the current research is limited. The method consists of multiple equations to be solved. The transmittance of the equations to a data sheet is time-consuming. Also, several mutations are needed to incorporate soil sealing parameters. The model only takes into account the buildings materials. Soil sealing could be incorporated by changing the fraction of evaporation. In addition, the net radiation has to be modified as the spectral properties of bare soil and vegetation differ from sealing materials.

MORUSUS, Bohnenstengel 2011

The model uses a sophisticated surface energy balance scheme to represent urban surfaces. MORUSES represents the parameter input in the model of Met Office Unified Model, MetUM (Porson et al, 2009b,c). A slab approach and 2D geometry are used to represent building geometry on the energy balance. The model is a so-called two tile model; one tile represents the screen-level, the other tile represents rooftops. The article tries to demonstrate that the model is able to represent the city temperatures. Secondly, the aim is to identify processes which produce the diurnal cycle.

MORUSES uses a tiled surface-exchange scheme, where the city is represented by two type of tiles: a tile for roofs and a tile for the street canyon.

Application

The model was used to simulate the effect of the urban surfaces on local climate. In this case in London, the temperature difference [K] between local temperatures in the urban area and temperatures if all surface were covered with grass were simulated.

These results are used to set up the urban boundary layer structure. Also, the temporal and spatial variation of the UHI is then simulated.

Model assumptions

- The model exists of long, parallel, flat-roofed buildings with roads in between. Parameters should be chosen carefully, so the model represents a real city.
- Anthropogenic heat is a constant value of 18W/m^2.

Bohnenstengel *et al.*, (2011) performed a case-study in London. The air temperature at a height of 1.5 m was determined by the model. The authors assume a measurement error of 2 K, due to 'limited spatial representativeness'. The UHI$_{max}$ is around 5 K, while daytime UHI is up to 1 K. The expected uncertainty of the MORUSES model lies between 1.3 and 1.5 K.

Steeneveld et al. 2011

The model presented by Steeneveld *et al.* (2011) is an empirical relation, achieved from hobby meteorology records and weather station data. The field data cover the temperature in multiple cities in the Netherlands, spread through the country. The UHI is determined as the difference between the city temperature and the rural temperature, measured at a local weather station in the vicinity of the city in question.

The maximum UHI intensity during a diurnal cycle was determined. The UHI was then linked to greenness, surface water availability and population density. The green and water cover fractions of the different cities where estimated by assigning pixels in aerials photographs to respectively vegetation and water. This method is similar to automated mapping techniques, in which a pixel is assigned to a certain category according to its spectral (and spatial in object based imagery) properties. The green percentage is then plotted against the UHI$_{max}$ after which a regression relation can be determined (Figure C).

Two relations are shown, the 95 percentile (in black) and the median (grey). The distribution of the UHI$_{max}$ intensities of all sampled days - which ranges from 211 days for some cities to 2167 for others – determines the 95 percentile; 95% of all the values falls within the range from zero to this value, and the mean; the UHI$_{max}$ value of the sample number that is exactly half of all samples (so it is not the same as the average!).

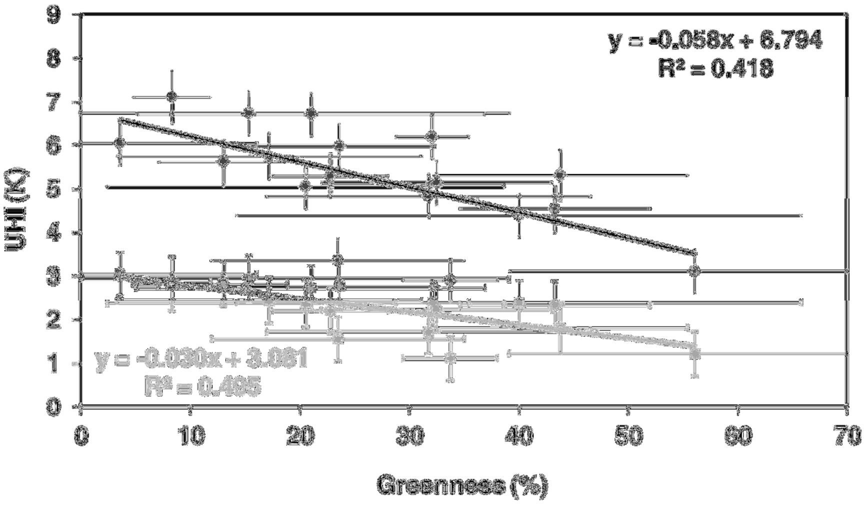

Figure C: The regression line of the percentage of green and the UHI$_{max}$ (Steeneveld *et al.*, 2011).

The method of Steeneveld et al (2011) cannot be used for this research for several reasons. Firstly, the relation determined by Steeneveld is between the UHI and vegetation or water. There is no direct link with impervious material, which makes the relation difficult to apply to the measurements in this research. Furthermore, Steeneveld uses data throughout the year, whilst in this research the extreme values are of most interest. The extreme values are expected during summer and heat-waves.

To overcome the first objection, a regression relation could be derived for sealed soil and the UHI$_{max}$. However, the UHI data available for Groningen are not sufficient to accomplish such a study. The GGD measured the UHI during the summer of 2012 by means of 44 weather stations. However, these stations are almost all within the inner city of Groningen. This region was purposely not chosen in this study, because the fraction of private garden area is relatively small.