Runoff changes due to urbanization: A review

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Abstract

Urbanization causes changes in the water balance. Focusing on runoff, the aim of this report was to determine how both the magnitude and the form of this component change with urbanization. Also, solutions for decreasing the possible problems related to an increase in surface runoff were examined. Solutions were studied for both a general European situation and for the specific case of the Netherlands. Already after converting a forested area into agriculture, the runoff becomes more prominent, at the expense of evaporation and infiltration. When developing further into an urban area, its importance increases even more. In the last few years, various scientists have come up with suggestions of reducing the risks caused by increased runoff. Some examples are increasing the infiltration capacity or storing the excess water in cities. Considering the predicted future climate scenarios, water storage seems to be the best option. In the Netherlands, expanding the areas for water storage is the main subject of governmental research at the moment. On top of that, researchers advice to cooperate more between different stakeholders when considering water management. The main findings are thus that runoff increases with an increasing imperviousness of the surface, and the best solution to avoid problems caused by this enhanced amount of runoff seems to be the storage of excess water in cities. This solution is valid for both a general situation and in the Netherlands.

Keywords: urbanization, runoff, flood protection, the Netherlands

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1 Introduction

1.1 Background

Urbanization is a well-known and important process nowadays. During urbanization, the population in cities and towns increases at the expense of the rural population. The portion of the global population living in urban areas has increased rapidly during the last century (figure 1). At the beginning of the twentieth century only 14% of the world population lived in an urban area. Already in 1992, this had increased to almost half of the world population (Meyer and Turner, 1992), and it did not stop afterwards. Within Europe, for example, the population has since then increased with 4% until 2012 (Bustos et al., 2015). Since population growth is one of the major causes of urbanization, an urbanization increase can be expected over that period of time as well (Antrop, 2004). Europe is not the only part of the world that has been noticing further urbanization after 1992. In other continents, urbanization has been taking place as well, resulting in the urban percentage of the world being 54% in 2014 (United Nations, 2015). And this increase in urban population is expected to continue until at least 2050.

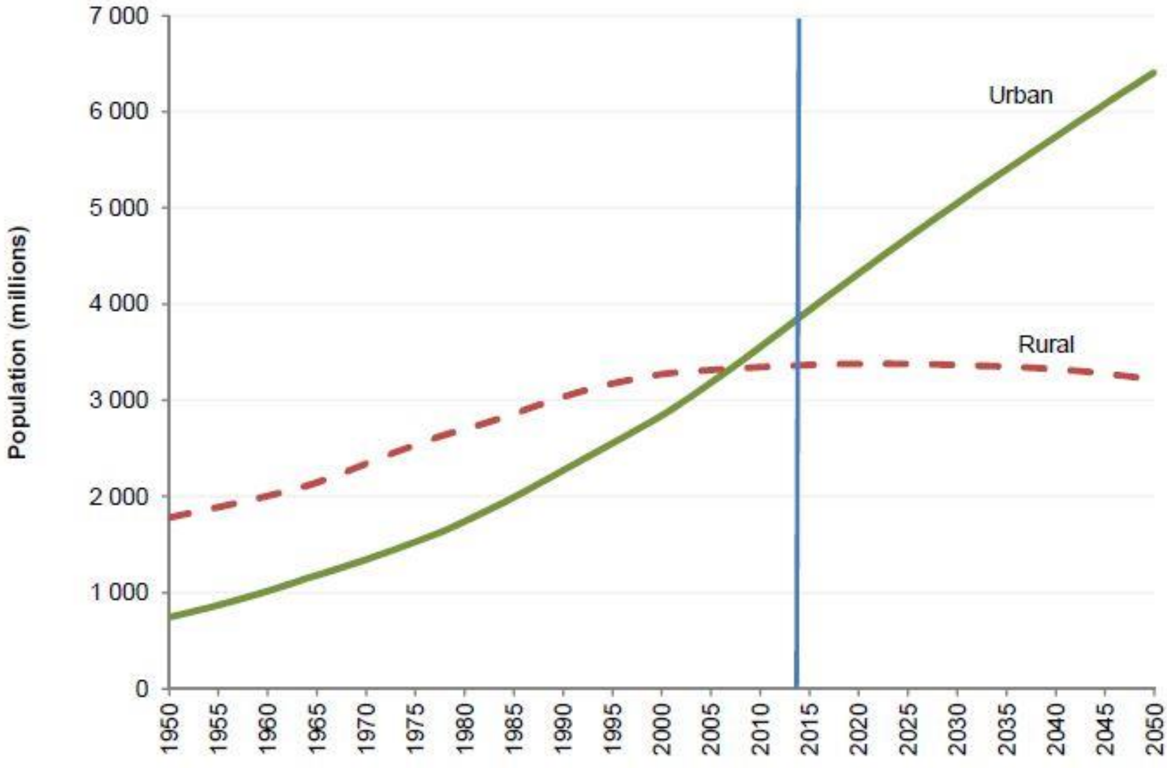

Figure 1. The world's urban and rural populations, 1950-2050 (from United Nations, 2015).

At the moment, the part of the total population living in an urban area is noticeably higher in developed countries than in undeveloped countries (Meyer and Turner, 1992). This is because there is a positive relationship between urbanization and the income per individual (United Nations, 2015). However, the most rapid urban growth nowadays is observed in the developing tropics (Meyer and Turner, 1992). In the future, urban areas will thus expand over the whole world, making it very important to look at the effects of urbanization on the human population, as well as on the environment. Even in countries with a decreasing population, the cities have been shown to keep slightly increasing (Antrop, 2004). Other than urbanization itself, non-urban development is taking place as well, causing the same changes in the landscape as urban development (Antrop, 2004; Bustos et al., 2015). This makes research about the effects of this changing landscape even more interesting.

Of course, urbanization has an impact on the economic situation of a country, for example, because of improved infrastructure and thus reachability of resources (Bustos et al., 2015). However, there are other, often forgotten, consequences of urbanization as well. For example, it harms the environment with air pollution from the traffic (Egondi et al., 2016). Also it can cause heat stress to the people living in the cities (Derkzen et al., 2015). Lastly, urbanization changes the water balance (Paul and Meyer, 2001; Niehoff et al., 2002; Burns et al., 2005, Branger et al., 2013).

The urban hydrologic cycle looks completely different from that of a nature area (figure 2). Important in the water balance of a natural situation are the fluxes of infiltration followed by further percolation into the ground water, the resulting ground water flow, and the transpiration flux from the vegetation (Todd, 1959). After urbanization, several components of the water balance may change, or even completely disappear. Research about this started around 1970, with for example Landsberg (1970), who states that the increasing imperviousness due to urbanization causes more rapid runoff. Over the last twenty years, research on this topic has been extended much further.

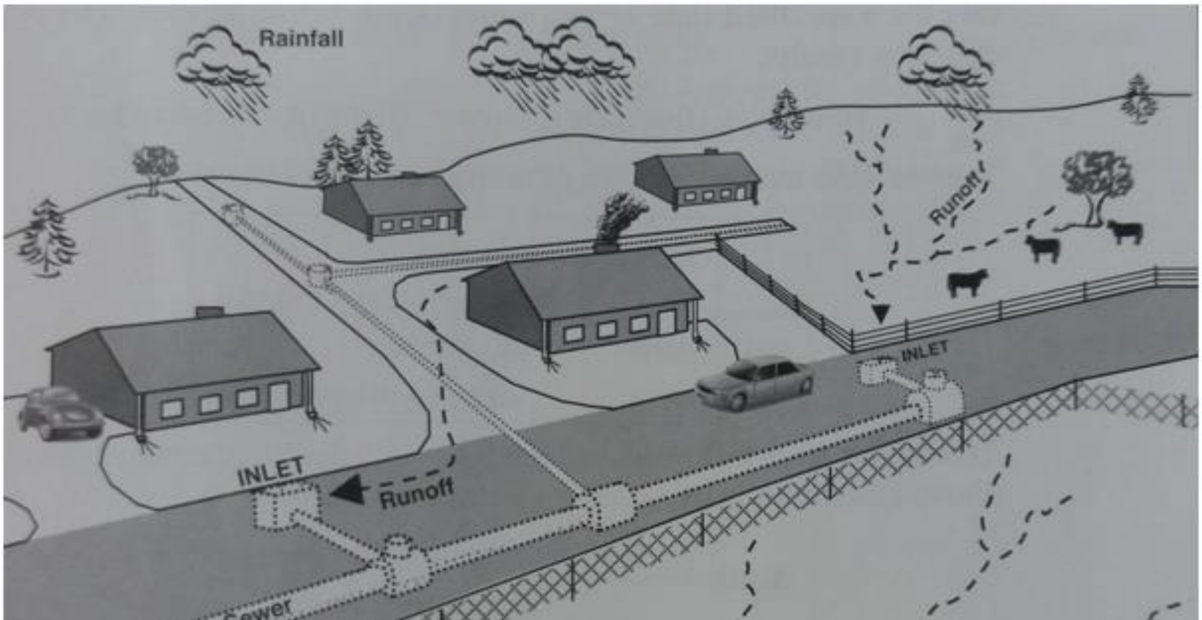

Figure 2. Urban hydrologic cycle. A combination of runoff from natural surroundings and man-made drainage systems, these runoffs come together at a single outlet. (from Bedient et al., 2012)

1.2 Aim

The aim of this research is to determine how urbanization influences the proportion of the different components of the water balance with a special focus on the runoff, and the risk of flooding as a possible consequence of it. Also, measures that can be taken to reduce this risk are examined, both for a general situation and for the Netherlands as a special case. Since the case study is about the Netherlands, I will focus on studies with similar climatic conditions while examining the effects of urbanization in general. However, later in the report I will include some examples of areas with other climates as well, to see the differences in effects of urbanization between various starting conditions. The Netherlands will be examined in more detail, because 60% of this country is located below sea level, which makes it rather unique with respect to water (Kabat et al., 2005).

2 Methods

This report is a literature based research. First, I used the book 'Hydrology and Floodplain Analysis' (Bedient et al., 2012), to obtain some general ideas about the water balance and about the possible effects of urbanization on it. Afterwards, the University Library of Umeå University, Google Scholar, Scopus, and Web of Science were my sources of information.

3 Results

3.1 Effects of urbanization on runoff

According to Todd (1959), the relative importance of the different components of the water balance in a natural situation is only dependent on the location. For instance, around the equator the evaporation can become much higher than at the poles because of the high temperatures at low latitudes. Also, precipitation is known to vary between different parts of the world. Despite these spatial variations over the globe, the different water fluxes are in balance if you focus on one specific location.

Generally, the first form of human development is agriculture. Since this is more common than completely forested areas nowadays, Hundecha and Bárdossy (2004) studied an afforestation scenario instead of a deforestation scenario in the Rhine basin, SW Germany. They did this by comparing the runoff in the current situation, containing 44% agriculture, with a modeled runoff in a situation of 100% forested area. A slightly more than double amount of forested area was found to result in an average decrease in peak flow of 14% during all seasons. Their explanation is an increase in evapotranspiration, higher infiltration rates, and interception of precipitation by the vegetation. The interception and the high transpiration in forests due to large rooting depths of trees also cause the seasonal and long-term mean runoff to decrease. Since my report is about increasing human development, the results of Hundecha and Bárdossy have to be inverted. With rising agriculture, the peak flow, as well as the seasonal and long-term mean runoff volume, will thus increase.

Naef et al. (2002) studied the change in runoff type in a catchment in Germany, using an example rainfall event of December 1993. During this rainfall event, 78 mm of precipitation was recorded over the whole catchment. According to Naef et al., the main runoff process in forests is lateral subsurface flow, which represents about 85% of the total runoff (figure 3). Saturation overland flow plays a role as well, but a very minor one. In a situation of agriculture however, Naef et al. indicate saturation overland flow to be the main runoff process accounting for more than 90% of the total runoff, with a very small contribution of lateral subsurface flow. When developing further into an urban area, Hortonian overflow is the only form of runoff. That the total runoff in the urban area is so low here, is because the figure is based on the whole catchment, and the urban area is considerably smaller than the forested area and the area with agriculture.

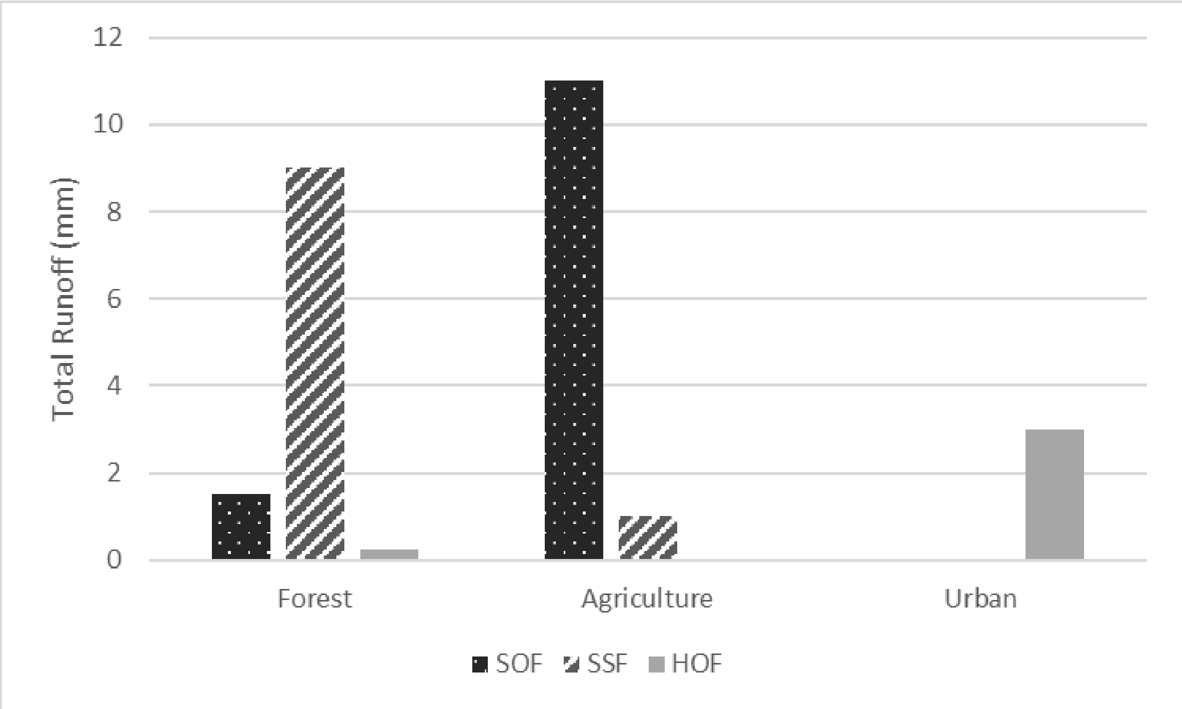

Figure 3. Total runoff (mm) for forest, agriculture and Urban areas, divided into saturation overland flow (SOF), lateral subsurface flow (SSF) and Hortonian overland flow (HOF), during an example rainfall event of December 1993 in Sulzbach, Germany (based on data from Naef et al. (2002)).

Meyer and Turner (1992) did a literature review on several environmental consequences of land cover change, and hydrology was one of their areas of interest. They state that changes in the water flow result from both intentional water withdrawals and from land cover changes like deforestation. The latter causes indirect changes in hydrology that can result in both a decreasing as well as an increasing effect on the runoff. In general, deforestation leads to an increase in annual flow. Meyer and Turner do not indicate how large this increase is. Water withdrawals cause the surface runoff to decrease. Irrigation is by far the largest element of withdrawal, accounting for about 75% of all water demand. Again, no numbers are given for the total amount of yearly withdrawal.

Arnold and Gibbons (1996) focused on the impact of impervious surfaces that accompany urbanization. Using an example from the Environmental Protection Agency of America, they give a general idea about what happens with the different components of the water balance with increasing urban area on a yearly basis. Paul and Meyer (2001) did a literature review using the article of Arnold and Gibbons and presented a clear image of what happens with increasing surface imperviousness (figure 4). It shows that in a forested area, runoff accounts for only 10% of the water output. When reaching a fully developed urban area with 75-100% surface imperviousness, the runoff is 5.5 times higher, caused by reduced evapotranspiration and infiltration.

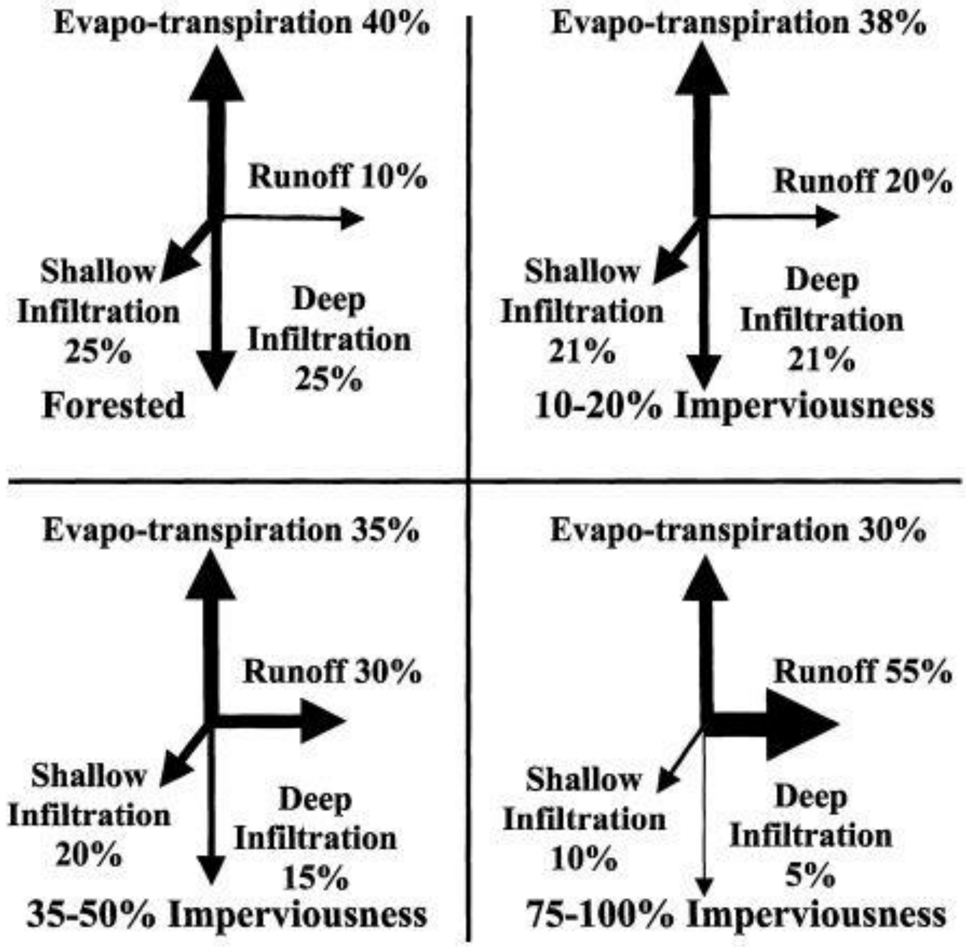

Figure 4. Changes in hydrologic flows with increasing impervious surface cover in urbanizing catchments (from Paul and Meyer, 2001).

Niehoff et al. (2002) also conducted a study in the Rhine basin, which they based on three catchments. First of all, they used a model to predict the land use changes that are likely to occur in the future. They then simulated the hydrological response to rainfall events for the current situation with an urban area of about 10%, as well as for various possible future land use scenarios. In all urban areas, they differentiated between densely settled areas and loose settlement by dividing each grid cell of their model in a sealed and an unsealed part. After running the model, they observed that different types of rainfall events result in different effects of urbanization on the peak flow (figure 5). All rainfall events result in an increase in both flood volume and peak runoff after urbanization. However, during an event with higher precipitation intensities, the effect of urbanization is larger. Both the peak flow and the total runoff volume increase more during such an event than during low intensity rainfall events. In this case for example, a precipitation event with 67 mm of rain in 4 hours resulted in an increase in peak flow of 6% with a 10% increase of urban area, and an increase of 28% with a 50% increase of urban area. Nevertheless, they also mention that these high intensity rainfall events usually occur very locally, and are therefore not of large importance for the formation of floods in the large river basins of Central Europe. Because the peak was not shorter after the modeled urbanization than in the current situation, the total flood volume increased as well.

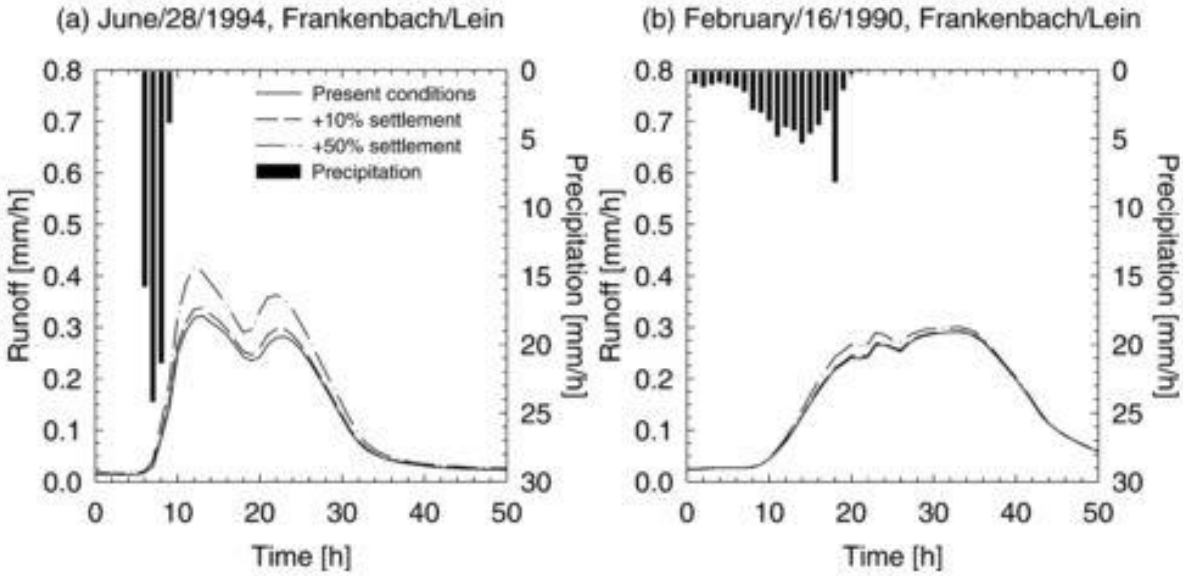

Figure 5. Hydrological impact of urbanization in the Lein catchment; simulation of two flood events as a response to (a) a convective storm event and (b) an advective storm event under present and scenario conditions (from Niehoff et al. (2002)).

Hundecha and Bárdossy (2004) (see above) also modeled a hypothetical scenario with a doubling of the current proportion of urban land use, as well as a future land use scenario based on the current urbanization trend. In the scenario with a doubled proportion of urban area, the simulation results clearly indicate an effect on the peak flow, with an average increase in discharge of about 9%. During all rainfall events, both the minimum and the maximum discharge increase and the average peak arrival time decreases. However, the peak flow increase is higher during the summer than during winter. According to Hundecha and Bárdossy, this is because the summer potential evapotranspiration is slightly higher in agricultural areas than in urban areas, so if the urban share of the catchment increases, the runoff will increase as well. Additionally, in the summer the storm events are generally preceded by dry soil conditions, meaning that there is more potential for infiltration than in the winter, especially at the beginning of the storm event. If the urban area then increases, the loss of infiltration capacity due to surface sealing becomes more important. In the predicted scenario for 2010, the urban area increased with only 12.8%. The corresponding increase in peak flow in this scenario was found to be fairly low, especially in the winter season. The average increase in discharge for this scenario is 1%. In this scenario again, there is an increase in discharge for all rainfall events, but surely not as much as in the doubled urban area case. Other than that, the decrease in average peak arrival time is not visible in all events. The increase in mean flow over the period 1983 to 1995 was simulated as well. This increase was found to be even smaller than for the predicted 2010 scenario, with an enlargement of only 0.5% on average.

The main goal of Brandes et al. (2005) was to determine the decrease in base flow due to urbanization in the Delaware River basin, USA. They relate this directly to the increase in stormflow and therefore make it extra interesting. Both the possible effects of drought during dry periods and the effects of flooding during wet periods are investigated. Impervious surface cover at the end of the measured time period ranges from 5% to 21% between the different watersheds. The hypothesis of Brandes et al. was that the base flow volumes will decrease in their examined watersheds, but this is only the case for two of them. For one of these two, this trend is not caused by human actions, but by a decrease in annual precipitation during the study period. The Cooper River watershed is the only watershed showing the expected trend in base flow. Therefore, this basin is examined a bit further. Brandes et al. did this for the period 1964 to 1984 and for the period 1985 to 2005. In the first period, the annual base flow as well as the annual storm flow increased. In the second, both of these flows showed a decrease. After correcting for the precipitation amounts, there was no trend in either base flow nor storm flow during the first period. In the second period, the storm flow stayed the same, but the base flow decreased, causing an overall decrease in annual streamflow volume. Considering all catchments, the stream base flow does not show a systematic decrease with urbanization, mainly due to water transfers from other basins and wastewater release into the watershed.

White and Greer (2006) investigated the effects of urbanization on the streamflow characteristics of the Los Penasquitos Creek in California. They divided their research period of 1965-2000 into three intervals, based on urbanization stage: <15% urbanization during the first period, 15-25% during the second, and >25% during the third. During the last two periods, both the annual minimum and the annual median discharges increased significantly. There was a slight increasing trend of maximum discharge during this period as well, but this was not significant. In the first period, there were wastewater releases into the streamflow, increasing its median annual discharges. The total annual runoff showed an increase of 4% between 1973 and 2000, representing an increase of more than 200% over the whole period. This increase was, however, marginally significant with a P-value of 0.06. On the other hand, the total dry-season runoff increased with high significance at an average rate of 13% per year. Peak discharges and flood magnitudes increase with urbanization as well, with the greatest increases for floods with low return intervals. The interpretation of White and Greer is that urbanization can significantly modify the stream characteristics in coastal Southern California.

Dietz and Clausen (2008) made a comparison between the hydrological effects of regular urban development and those of low impact development (LID) in Waterford, America, but I will come back to LID in more detail when I examine measures to decrease excess water in cities. With regular urban development, the storm water runoff volume shows to increase significantly with increasing impervious area. With an impervious area expansion from 1% to 32%, the annual runoff becomes 490 times larger.

Bedient et al. (2012) demonstrate an example of an urban hydrologic cycle, based on previous studies. There is still some surface runoff over the natural surroundings, but man-made drainage systems are becoming an important form of discharge as well. When the city develops further, the natural surface runoff might even completely disappear and man-made drainage systems will become the only form of water transport out of the city. These man-made drainage systems can be either underground through sewers, or above ground through concrete channels. In contrast to the naturally meandering streams and rivers, channels are normally straight. Also, the resistance of concrete channels is normally lower than that of natural streams and rivers. Both of these factors will shorten the runoff time and increase the peak flow downstream (figure 6). In a natural system, the hydrograph will show a large lag time before the peak discharge, and the amount of water at the time of the peak is relatively low. In a fully developed urban drainage system however, opposite conditions apply. The time before the peak is short and the water flow during the peak is considerably higher than in a natural situation.

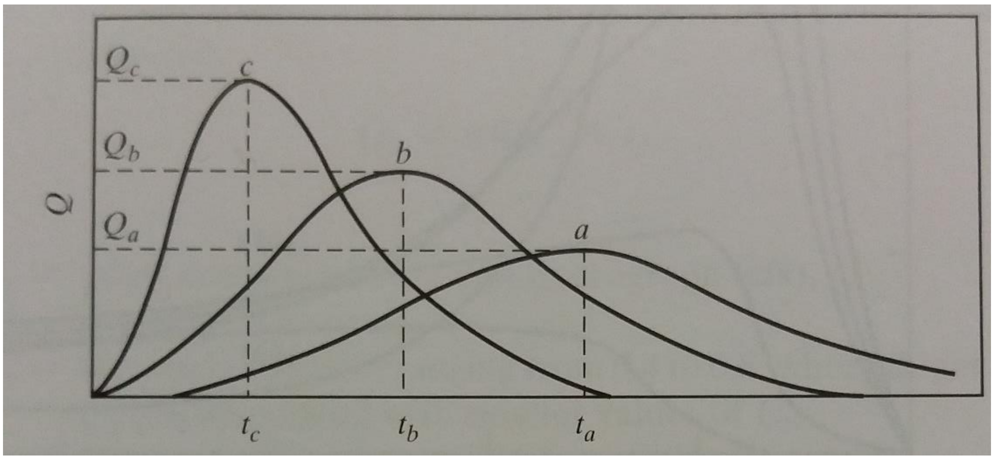

Figure 6. Hydrographs for different stages of development. a represents a natural watershed, b is partially developed, and c is a fully developed watershed (from Bedient et al., 2012).

Branger et al. (2013) conducted their research in a peri-urban catchment near Lyon in France, with an increasing level of urbanization when moving downstream. The goal of their research was to perform long-term, continuous simulations. After having those, they compared the effects of the different levels of urbanization on the runoff. The general trend that they found when applying the various land uses, is that with higher levels of urbanization, the mean discharge increases. For example, the catchment with an estimated impervious area of 2-6% has a mean discharge of 0.046 m^3/s, while the catchment with an estimated impervious area of 8-29% has a mean discharge of 0.600%. Also the length of the drought periods decreases.

All above treated studies were conducted in Europe, or in areas with a climate comparable to that in Europe. For the comparison with other starting conditions before urbanization, I will now treat a few papers from parts of the world with completely different climates.

In 1987, Sternberg conducted a research on surface runoff, based on Amazon River flood observations. Sternberg found that urbanization has an effect on the streamflow in at least two ways. First of all, deforestation has a direct effect by taking away the transpiration. Secondly, changes in soil characteristics, particularly its infiltration capacity, have an indirect effect on the water balance. The combined effect of lowering both transpiration and water storage in the soil, raises the height of flood levels. However, in case of low water flows, these two effects might counter balance each other and cause a lowering of the peak flow. Therefore, in dry periods, the discharge might be reduced even further than it already would be. Not only the height of the peak flow was investigated, the length of it was examined as well. However, the length does not show any significant change over time. Also the timing of the floods does not change. Something that does change, together with the higher discharges, is the sediment load. More sediment is transported downstream, which can eventually cause a blockage of the river stream. However, despite all these effects of urbanization, the overall effects on the Amazon River are small. This is because only a very small part of the Amazon is inhabited by humans.

The study about the Amazon was mostly focused on possible increases of flooding. Opposite to that, Micklin (1988) and Kotlyakov (1991) did their researches on the reduction of water in the Aral Sea. The Aral Sea is a terminal lake, which means that it has no outflow. Its water level is determined by the balance between water influx, caused by river inflow, ground water inflow and precipitation, and water efflux in the form of evaporation from the surface (Micklin, 1988). According to Micklin, between 1960 and 1987, the water level had fallen 12.9 m, the area decreased by 40% and the volume by 60%. Kotlyakov mentioned an even further decrease of more than 14 m, compared to the 1960 level, by 1990. Both Micklin and Kotlyakov expect the Aral Sea to shrink into a small lake and they think human actions are the main cause of this water reduction. The previous bottom of the lake, now exposed to the surface, is causing salt and dust storms. Also, the biological activity in and around the lake has decreased. But not only the environment is disturbed, the population living in the area around the Aral Sea is affected as well. Since fishing is no longer a proper source of income, several fishing villages have been abandoned (Micklin, 1988). Another effect is a decrease in human health. Highly toxic chemical pesticides accumulate in drainage waters and eventually contaminate the local drinking water (Kotlyakov, 1991). Finally, the shrinking of the water body will cause evaporation to decrease enough for making the water balance in equilibrium again. However, this is not expected to happen for decades (Micklin, 1988).

3.2 Measures to decrease excess water

Because an increase in runoff due to urbanization can cause flooding, it is important to find solutions to decrease the excess water in cities. Several studies have been conducted about possible methods to deal with this problem. I will only treat studies from this century, to find out recent views on the topic.

As mentioned in section 3.1, Naef et al. (2002) say that Hortonian overland flow (HOF) is the only runoff process in urban areas due to the low infiltration capacity (figure 7). HOF is a rapidly reacting runoff process, so in order to lower the storm runoff, part of the HOF has to be converted into slower reacting runoff processes like SOF. Consequently, the permeability of the soil has to be increased. Naef et al. suggest doing this by tillage, combined with plants having a high root density and a lush surface cover.

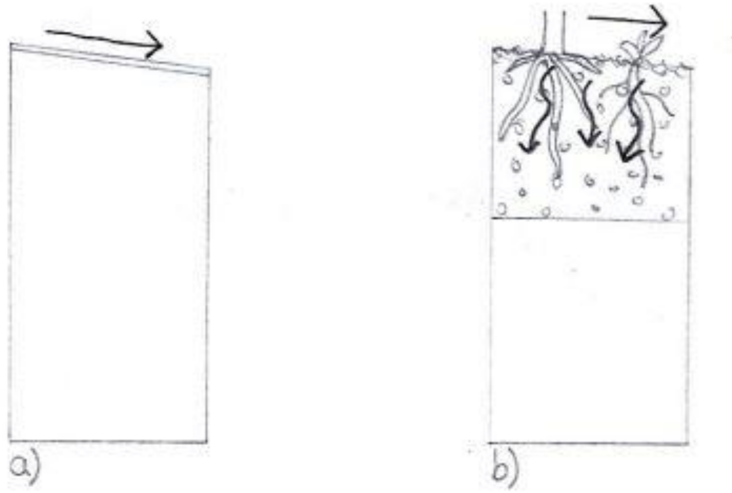

Figure 7. Difference in runoff type between a) an urban area, and b) an area with increased soil permeability (based on data from Naef et al. (2002)).

Van Roon (2007) discusses different case studies from Australia and New Zealand to check the effects of integrated urban water cycle management. She does not only look at reducing storm runoff, but also at more sustainable ways of using water in cities and creating less contamination. Commonly, improved urban sustainability leads to higher storm runoff. This has to be controlled to reduce downstream bank erosion, flooding, and ecosystem degradation. Van Roon states that reduced storm runoff can be achieved by creating hydrological neutrality. This can be done by rainwater reuse and by increasing the two natural processes of infiltration and evapotranspiration. An increase in infiltration and evapotranspiration can be obtained by changing the vegetation type in for example city parks. Also ecoroofs are proposed. However, storm water recycling should not become too efficient either, because then the discharge to natural receiving waters might not imitate the natural predevelopment hydrological regime anymore. To control this problem, computer models are often used nowadays for balancing the water cycle in and around urban areas to a natural regime. According to Van Roon, the most sustainable way of using water can be obtained by changing the spatial scale of water management from regional to local. This will limit unwanted changes to the natural hydrological regime caused by urbanization. In addition, the demand for external water supply will be reduced.

Dietz and Clausen (2008) (see section 3.1) indicate that LID is based on imitating the predevelopment hydrology of an area. Example measures to accomplish this are building in clusters, and creating grassed swales, rain gardens and pervious pavements. In the LID subdivision, the runoff volume did not change significantly over time, even though the total impervious area here increased from zero to 21%. As mentioned earlier, with a slightly larger increase in impervious area in the subdivision with regular development, the annual runoff became 490 times higher. The conclusion of Dietz and Clausen is that the lack of change in runoff volume with increasing impervious area in the LID subdivision, can only be attributed to the LID storm water management techniques in this watershed. These techniques reduce the overall impervious footprint, decentralize the water treatment, and increase the infiltration of water into the soil.

SWITCH is a project about sustainable water management in the 'City of the Future'. This project is still proceeding, but the findings from 2006-2011 have been documented by Howe et al. (2011). SWITCH covers cities in four continents and at different stages of development. As to flood control, they suggest the collection of rainwater from roof surfaces to reduce the volume of runoff that has to be managed by the drainage system of the city. This solution applies to all rainfall events. For heavy rainfall events, additional measures have to be taken. Conventionally, cities use drainage channels and underground pipes to get rid of the water as quick as possible. However, this conventional approach has some issues. If there is too much rainfall, combined sewers can overflow. On top of that, high velocity runoff causes erosion and increased sedimentation downstream. Another con is that fast drainage out of a city upstream can cause flooding downstream. Howe et al. suggest to view storm water not only as a hazard, but also as a potentially valuable resource. With this new view, they tried out several different solutions in different places of the world. For example, in Germany, they managed the runoff from roads in 'pocket wetlands' to minimize the hydraulic load of the combined sewer system. In the UK, they designed low maintenance versions of green roofs (figure 8). These roofs reduce surface runoff, and at the same time they have a positive effect on the environment. However, Howe et al. do not mention how large this effect is. The main finding of the SWITCH project about storm water control is that the problem nowadays lies not in technical issues, but in decision making. Howe et al. think that we should start seeing storm water as a possible valuable source of water supply, as well as a physical amenity for urban areas.

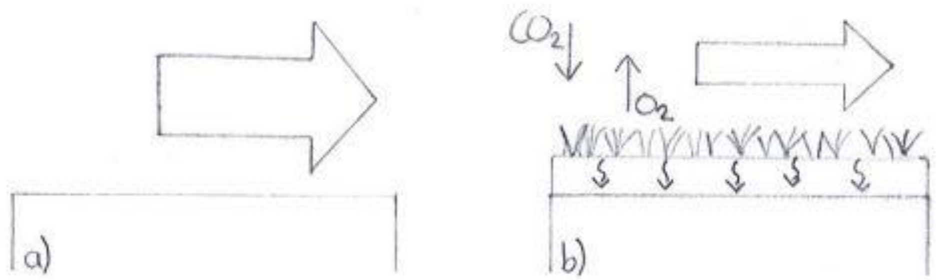

Figure 8. The runoff from a) a normal roof, and b) a green roof. The green roof also helps reducing the CO2 concentrations in the atmosphere (based on data from Howe et al. (2011)).

3.3 Measures in the Netherlands

Already in the 13th century, Dutch water boards started to build flood defenses and they have been maintaining them ever since (Slomp, 2012). Several scientists have done research in the Netherlands, but also their own government has assigned different institutions to think about ways to reduce flood risks. The first report I will examine, is that of Ministerie van Verkeer en Waterstaat (2000). Ministerie van Verkeer en Waterstaat is the Dutch Ministry of Transport and Water Management. They have to make sure that all inhabitants of the Netherlands are safe, also if they live below sea level and/or close to rivers. First of all, they suggest to make the general population more aware of the possible dangers of water. If people are more aware of the problem, they will be more willing to cooperate when the government wants to make a change in the landscape around them. Also, with online platforms, companies as well as individuals, can participate in the discussion about new proposals. One of the actual changes in land use that the ministry wants to make, is using more space for water storage. In earlier times, large water bodies were available for water storage throughout the year. In case of heavy rainfall events, these water bodies would fill up a bit more than usual, but nothing dangerous would happen to the population. However, due to a considerable increase in population, the areas where these water bodies were situated are now used for other purposes. Dikes have been expanded to defend those areas, but with increasing runoff coming from upstream, this will not continue to be a proper protection against the water forever. Furthermore, behind higher dykes, more water can be stored, so if this higher dyke breaks, the effects will be more dangerous as well (figure 9). For this reason, it is proposed to find different solutions than just getting rid of the water as quick as possible during times of high precipitation, especially in upstream regions. These upstream regions can be in the eastern part of the Netherlands, or even further up in other countries. Because the Netherlands is situated in a delta area, the government has made arrangements with surrounding countries to protect their inhabitants. Within the Netherlands, adjustments will be made along the coastline, around rivers, and in the IJsselmeer. Also, when new building projects start, the 'watertoets' (water test in English) will be applied to check whether the building project is not likely to have negative influences on the water regime in the future. The executive companies have to present all possible consequences of their project to safety and water problems. In the end, decision makers of different levels have to cooperate and make sure that the new measures will have a positive influence, both on the local and on the regional scale.

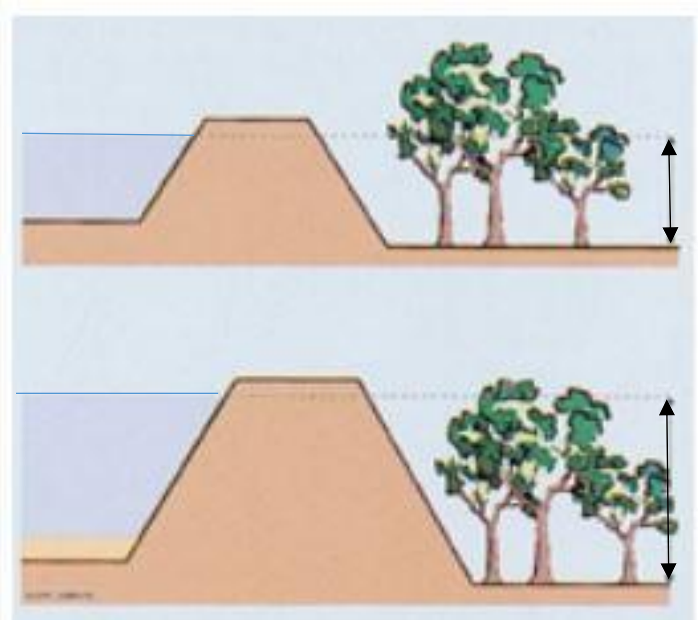

Figure 9. Two different heights of dykes. The lower image shows a larger dyke, holding more water behind it. All this water will reach the people living behind it in case of a dyke-break (based on data from Ministerie van Verkeer en Waterstaat, 2000).

The ‘Deltacommissie’ (Delta Committee in English) is one of the groups assigned by the government to come up with recommendations about water management. This committee is a combination of both scientists and politicians. In 2008, they presented their findings in a report (Deltacommissie, 2008). They state that the current standards of flood protection are out of date and must be raised, and even these current standards are not being met in the whole country. Therefore, the Netherlands must hurry up with realizing newly recommended measures. The Delta Committee came up with twelve recommendations for the future. I will only treat a few of them, because some recommendations are about the protection of coastal areas against sea level rise. This is not what my research is about. One of the advices of the Delta Committee that is important for my research, is the increase of the flood protection level around rivers. They advise to raise this by a factor 10, preferably before 2013. The increase of the flood protection level means improving the dikes. This can be done by either making them higher, wider, or both. The Delta Committee also comes up with plans for new urban development. They say that the decision of whether to start building in low-lying areas with a high risk of flooding has to be based on a cost-benefit analysis for all parties. The costs that occur because of building in high-risk areas should be borne by those who benefit from building there. Besides that, new development in areas that are unprotected by dikes must not hinder the river discharge or the future water levels in the lakes. The government should give information, impose building requirements based on the particular situation, and warn for floods, but eventually the residents themselves are responsible for the measures that might be needed to avoid dangerous situations.

In the major rivers area, the ‘Ruimte voor de Rivier’ (Room for the River) and Maaswerken (Meuse Works) programs are attempted to be implemented as soon as possible. The Room for the River program is about letting space next to the river flood on purpose during times of high discharge. This program was setup recently, because higher drain volumes are expected from upstream due to urbanization and thereby hardening of the surface (Ruimtevoorderivier, 2016). Meuse Works is a project of Rijkswaterstaat, a part of the government responsible for the main infrastructure facilities in the Netherlands. The Meuse Works project is brought to life to prevent the river Meuse from flooding, make it easier for large ships to sail on the Meuse, and create 1800 ha new nature. Rijkswaterstaat wants to obtain this by increasing the strength of the wharfs, making the river itself deeper and wider, digging special trenches for times of high water levels, and lowering the floodplains (Rijkswaterstaat, 2016). A new project that the Delta Committee suggests to start is that of a ‘closable-open’ Rijnmond system (Deltacommissie, 2008). This means that during extreme discharges in the Rhine and the Meuse, part of the water will be re-routed via the south-western delta. The newly suggested system offers good prospects for flood protection, fresh water supply, urban development, and nature development all combined.

The before mentioned Meuse Works project is not the only new item of Rijkswaterstaat. They also produced a report about flood risks and water management in the Netherlands (Slomp, 2012). In old times, farmers used to own the floodplains. Nowadays, nature conservation organizations and the state government are the owners of a large part of the floodplains. They need space to be able to improve the transportation capacity of the rivers. Additionally, with less farming on the floodplains, shrubs and trees can start growing, which slows down the water flow in case of large discharge periods. A new project, called The New Delta Program, will be the first project which is not based on a past disaster, but is mainly considering future economic growth and climate change. The different parts of the project will be carried out from 2020 onwards. Something else Rijkswaterstaat has been working on, which is particularly interesting in a situation of continuing urbanization, is spatial planning. Since 1996, all construction in flood plains of the lowest lying areas of the Netherlands has been prohibited. In 2009, this area was extended even further. The reason for prohibiting construction in flood plains in the lower lying areas of the Netherlands is the increasing chance of floods in the future. To make sure that there is still enough space to accommodate people, experiments with floating houses have been carried out. To prevent flooding in areas where it is still allowed to build, separate systems are now being used for the removal of sewage and access rainfall. Something that might be a little bit unexpected in a land such as the Netherlands, is that it is impossible to get a flood insurance for your home or business. But even though this sounds strange at first, it actually improves the safety of the country's inhabitants. Every citizen has to pay taxation for maintenance and reconstruction projects, which makes the flood protection standards very high. Other than general protection against flooding, the government also organized a major flood risk exercise in 2007, to practice communication and fast response in a situation of high risk of flooding. The outcome of this exercise was that the river areas can be evacuated in time, but the densely populated areas along the sea coast cannot. Therefore, a national evacuation strategy is developed later by the Ministry of Safety and Justice (Ministerie van Veiligheid en Justitie, 2014).

Now that I have examined different institutions related to the Dutch government, I will also treat several reports written by scientists. The first report is that of Van der Brugge et al. (2005). They argue that things like housing, industry, infrastructure and agriculture have had a negative influence on the water system in the Netherlands. This is because the increasing societal demands caused water engineers to focus on fast drainage of redundant water, canalize rivers, and construct dikes and dams. This works for a short time perspective, but in the long-term this is not sustainable. Van der Brugge et al. suggest that water managers should no longer try to optimize one particular utility, but they should cooperate with different stakeholders who represent various perspectives. In order to make a fundamental change in the water management strategy, representatives from multiple scales (local and regional) have to work together. Already since the 1970s, some change has been noticed, but it has to develop even further to obtain sustainable water management in the future.

Van de Ven et al. (2011) strive to create an approach for water robust urban development. First of all, they studied flood and drought mitigation practices from all over the world. This gave them many options to choose from. After that, they presented a three-step process, which gives decision makers the opportunity to choose the best option for their own situation. The first step of this three-step approach is a vulnerability analysis. During the vulnerability analysis, the sensitivity of the area to climate impacts, as well as the already existing protection measures are analyzed. Step two is the selection of a strategy to reduce vulnerability. This involves selecting and combining different protection measures. The selection process that Van de Ven et al. propose is based on the concept of vulnerability reduction. In this concept, there are four important capacities: the threshold capacity, the coping capacity, the recovery capacity, and the adaptive capacity. The threshold capacity is about damage prevention, the coping capacity about damage reduction, the recovery capacity is based on damage reaction, and the adaptive capacity handles with damage anticipation. Usually, if an investment is made in one capacity, efforts of one or more other capacities are decreased, resulting in an overall increase in vulnerability. Therefore, it is important to relate newly proposed strategies to already existing ones and to the local conditions. This is done in step three, where the measures that will be taken are selected. A set of measures is eventually chosen based on an agreement between all stakeholders. In the process of urban development, three phases seem to be crucial for creating a water robust environment. The first phase is the spatial planning phase, the second phase is the design and building preparation phase, and the last phase is actually an interaction between two phases, namely the moment of transfer to the maintenance phase. In all these phases, the three-step vulnerability reduction process has to be carried out. Only in this way, the knowledge of the previous phase is transferred onto the new group of stakeholders. The main advice of Van de Ven et al. is to make the process of water robust urban development a collaboration between different stakeholders, and involve water vulnerability in different phases of the development.

Hoss et al. (2013) based their research on a new water management strategy that was proposed by the Dutch government in 2009. Because urbanization has caused the value of what has to be protected to increase remarkably in the last few decennia, the government suggested a strategy based on Multilayered Safety (MLS). The first layer is the prevention of flooding, which stays the most important part of the water safety policy. However, because a flood can never be completely excluded, the second and third layer are based on reducing the negative consequences of a flood. The second layer aims at sustainable spatial planning, and the third layer focusses on crisis management (Rijksoverheid, 2009). In their study, Hoss et al. assess the effect of the MLS strategy and evaluate optimal combinations of measures. They introduce a framework to make it easier for decision makers to choose which measures are most suitable for their situation. The framework gives an overview of all available MLS measures and ranks them by type of effect and scale of impact. This framework can be used by decision makers over the whole country. In their case study about Dordrecht, they evaluate the cost-efficiency of MLS measures to enable an optimal combination of measures for the city of Dordrecht itself, but also for other parts of the country coping with similar problems. Dordrecht is chosen, because most of Dordrecht's urbanized area is located below sea level, just like the most densely populated part of the whole country. Currently, the flood protection of Dordrecht relies mainly on the dike ring and is thus strongly focused on prevention. Hoss et al. studied the cost-efficiency of different measures on just one neighborhood, and on the whole area protected by the dike ring. They concluded that there is a noticeable difference between the two, and it is thus important to consider the size of your area of interest. For smaller areas, consequence-reducing measures can be cost-effective. However, the only consequence-reducing measure that seemed cost-efficient for both the whole dike ring area and the neighborhood, was the placement of sand bags in case of flooding. The layer of prevention remains the most cost-efficient in Dordrecht, because of the high initial prevention level due to investing in this for centuries. Overall, the study of Hoss et al. shows that MLS is not cost-efficient if major investments in one strategy have already been made. Therefore, they suggest to use MLS as an addition to the prevention-based flood risk management in the Netherlands, rather than replacing the existing management by MLS.

Kaufmann et al. (2016) published a research about the implementation of MLS in the Netherlands and Flanders. I will reflect only on the implementation of MLS in the Netherlands. Kaufmann et al. did not focus on one city, but considered the whole Netherlands. They as well state that the MLS approach is not very cost-effective on a large scale. However, on regional level it might be different. The regional management approach has been more open with less rigid and lower safety standards. Therefore, past investments have been lower in regional defense structures and adaptive spatial planning strategies are already more common. This means that consequence-reducing measures could be more cost-effective at regional scale than strengthening the defense infrastructure. Kaufmann et al. say that the reason of MLS not working well on large scales in the Netherlands, is that institutional developments and past investments have resulted in a relatively closed policy arrangement. It is very difficult to make changes in such a closed management system.

4 Discussion

4.1 Urbanization

4.1.1 How does it affect runoff?

The general trend is that an increasing amount of human development causes the runoff to rise. This starts already when turning a forested area into an agricultural landscape (Naef et al., 2002; Hundecha and Bárdossy, 2004). If the agricultural landscape then develops further into an urban area, the runoff tends to increase even more due to an increasing imperviousness of the surface (Sternberg, 1987; Paul and Meyer, 2001; Niehoff et al., 2002; Hundecha and Bárdossy, 2004; White and Greer, 2006; Dietz and Clausen, 2008; Bedient et al., 2012; Branger et al., 2013). Within the land use categories of agriculture and urban area, the intensity of human development has to be taken into account as well. For example, not all cities have the same level of imperviousness (Niehoff et al., 2002). You can thus not state that when changing the landscape from a forest into an urban area, the runoff always changes with the same amount or percentage. With an increasing imperviousness inside the category of urban area, the effects on the runoff will be larger (Hundecha and Bárdossy, 2004).

The form of runoff changes as well. In a forested area, the lateral subsurface flow plays an important role, while in the stage of agriculture saturation overflow is the main runoff component (Naef et al., 2002). In a fully developed area, Hortonian overflow, but also water transportation through sewer systems below-ground transport the water out of the area (Naef et al., 2002; Bedient et al., 2012).

According to Niehoff et al. (2002), the largest increase in peak flow due to urbanization is noticed during high intensity rainfall events. Hundecha and Bárdossy (2004) state this largest increase to be during the summer. Although there might be a slight difference between these two conclusions, they do overlap. High intensity rainfall events are more likely to occur during the summer than during winter (Karl et al., 1995), so both articles refer to the same time of the year in which the increase in peak flow is largest. As for the location, whole Europe is experiencing an increase in heavy rainfall events during the summer, with the largest increase in Eastern Europe (IPCC, 2013; Madsen et al., 2014), so eventually the effects urbanization will probably largest in Eastern Europe during the summer months. That in the rest of the articles the timing of the largest increase in runoff is not mentioned, is because only yearly volumes were used in those. When comparing different articles, it is thus important to take into account the time scales used by the various researchers.

Even though the peak flow increases during summer after urbanization, the general idea is that the total runoff tends to decrease in this season (White and Greer, 2006; Jacobson, 2011; Branger et al., 2013). However, White and Greer (2006) found the opposite. On top of that, Branger et al. (2013) noticed a decreasing length of the dry periods. This implies that the effects of urbanization on dry season runoff should not be generalized anymore, but every specific situation has to be examined individually.

Not only the level of development, the type of rainfall event, and the time of the year determine the effects of urbanization on the runoff. Urbanization can lead to a considerable variety of consequences for the runoff due to the conditions existing before the start of human development, as shown by Sternberg (1987), Micklin (1988) and Kotlyakov (1991). For example, urbanization in the Amazon seems to result in a similar alternation of the water balance as in the European situation. However, the scale on which it affects the surrounding environment is very different. Since only a very small part of the Amazon is inhabited by human population, the effects of urbanization on the whole catchment are very limited (Sternberg, 1987). In Western countries, however, both the total population density and the part of the population living in an urban area are already rather high (Meyer and Turner, 1992; United Nations, 2015). Therefore, the effect of urbanization on the water balance in Europe is much more noticeable than in the Amazon. If urbanization occurs upstream, in Europe this will have a considerable effect on the cities downstream, while in the Amazon the effects will be evened out by the natural surroundings (Sternberg, 1987; Howe et al., 2011, Bedient et al, 2012). Other than the influences of population density, the initial distribution of the water balance components plays a role as well. For example, the area around the Aral Sea has been very dry since human history, but after urbanization the Aral Sea itself began to lose water as well (Micklin, 1988; Kotlyakov, 1991). The effects of urbanization on the water balance in dry parts of the world can thus be opposite to the effects in Europe.

4.1.2 Why does runoff change?

The main cause for the increase in surface runoff after urbanization is the reduction of both evapotranspiration and infiltration (Arnold and Gibbons, 1996; Niehoff et al., 2002; Hundecha and Bárdossy, 2004). If these two components decrease, only the runoff is left to get rid of the water. One of the reasons for the decrease in those components is an increase of surface imperviousness (Arnold and Gibbons, 1996). Surface imperviousness directly reduces the infiltration into the soil. Indirectly, if there is less water in the upper layer of the soil, it will cause the evapotranspiration to decrease as well. The decrease in soil infiltration has the largest effect in the warm summer months, because during this time of the year, the potential for infiltration is highest due to the initial dry conditions of the soil (Niehoff et al., 2002; Hundecha and Bárdossy, 2004).

Another reason for decreased evapotranspiration in cities is that there usually is no or very little vegetation. Therefore, the actual evapotranspiration will be considerably lower than the potential evapotranspiration. Since the potential evapotranspiration is higher during summer than during winter, the lack of vegetation in cites has its largest effect during the summer season (Hundecha and Bárdossy, 2004).

Also, the change in runoff type, mentioned by Bedient et al. (2012), has an effect on the peak flow. The runoff through man-made drainage systems goes faster than through naturally meandering streams (Bedient et al., 2012). Most of the water will thus arrive downstream within a short time interval, instead of being spread out over several hours. The man-made drainage systems have again most impact during the summer. This because high intensity rainfall events can cause the sewer system to overflow, resulting in a larger surface runoff (Niehoff et al., 2002).

The unexpected increase in dry season runoff (see chapter 4.1.1) can be related to, for example, a wastewater treatment plant or other low-volume discharges inside the catchment (Brandes et al., 2005). Furthermore, inter-annual variation in precipitation can play a role (Branger et al., 2013). If summer precipitation is high during one of the later years of the study, the dry season runoff might show an increasing trend, having nothing to do with urbanization. Lastly, excess irrigation water coming from another catchment nearby can increase the runoff in the catchment of interest (Brandes et al., 2005; White and Greer, 2006). It is thus important to keep in mind the surroundings of the catchment you are investigating as well. Only focusing on your own catchment might result in wrong conclusions.

4.2 Best ways to reduce changes in the urban hydrological cycle

4.2.1 General situation

The conventional approach of reducing floods was to get rid of excess water as quick as possible (Howe et al., 2011). Nowadays, the measures are more sustainable. For example, several studies proposed to decrease the runoff by increasing infiltration and/or evapotranspiration (Naef et al., 2002; Van Roon, 2007; Dietz and Clausen, 2008). This seems a good idea, since these are the two components that tend to decrease with urbanization (Paul and Meyer, 2001). The infiltration can be increased by tillage, applying a lush surface cover, or planting vegetation with high root density (Naef et al., 2002). Changing the vegetation type can also increase the evapotranspiration (Van Roon, 2007). In the case of agriculture, all above mentioned options are possible. In a city however, changing the vegetation type of plants in green areas into plants with higher root densities seems to be most reasonable. This because there usually is no space for tillage in cities, and lush surface cover will not be appreciated by people with cars or bikes either.

Even though it is good to have ideas about reducing the runoff, this should not be done at the expense of the environment or of cities downstream. Therefore, several researchers proposed storing more water in cities (Van Roon, 2007; Dietz and Clausen, 2008; Howe et al., 2011). In this way, not only the runoff will be reduced, but it also provides opportunities for reusing the water if needed (Van Roon, 2007; Howe et al., 2011). Storing the water can be done in several ways, like building ecoroofs or creating grassed swales and rain gardens (Van Roon, 2007; Dietz and Clausen, 2008; Howe et al., 2011).

4.2.2 The Netherlands as a special case

Because of the low position of the Netherlands compared to sea level, their government is very active in water management (Ministerie van Verkeer en Waterstaat, 2000; Deltacommissie, 2008; Slomp, 2012; Ministerie van Veiligheid en Justitie, 2014; Rijkswaterstaat, 2016; Ruimtevoorderivier, 2016). All reports related to the government indicate that the Netherlands needs to reserve more space for water. This suggests that, due to the generally low position and minor slopes in the country, drainage cannot be obtained fast enough to prevent flooding with the continuing increase of urban areas. The population of the Netherlands is already rather high, with 504 inhabitants/km^2 according to Statistics Netherlands (CBS, 2016). Therefore, it might become difficult to accommodate all these people after making more space for water. However, floating houses seem to be a good option of solving this problem (Slomp, 2012).

Scientists that conducted their study in the Netherlands suggest to be more collaborative in water management. This can be obtained either by working together with representatives of local and regional scales, or by cooperating between stakeholders of different phases in the urban development (Van der Brugget et al., 2005; Van de Ven et al, 2011). In both cases, it means that not only one party should be responsible for making decisions about water management, but several parties should work together to obtain the best results.

Consequence-reducing measures only seem to be cost-effective on small scales (Hoss et al., 2013; Kaufmann et al., 2106). However, the definition of small scale differs between different researches. Small scale can either mean neighborhood scale compared to a complete city, or regional scale compared to the full country of the Netherlands (Hoss et al., 2013; Kaufmann et al., 2106). A possible conclusion that can be drawn from this, is that consequence-reducing measures are cost-effective on the small neighborhood scale, become less effective on the city scale, again more effective on regional scale, and at country scale it again becomes less effective. On the other hand, Dordrecht was considered to be representative for the whole Netherlands due to most of its population living below sea level. Therefore, another possible conclusion is that when including both the part above and the part below sea level, the consequence-reducing measures are not cost-effective, but when you consider these parts separately it might become much more attractive.

4.3 Climate change

An increase in heavy rainfall events has already been noticed in both Europe and America, and in the future this rise is expected to continue even further (IPCC, 2013). During a heavy rainfall event, it is difficult to have an infiltration capacity high enough to absorb all the rainwater into the soil. Therefore, the increase in infiltration capacity, proposed by Naef et al. (2002) and Van Roon (2007), will not be enough to prevent flooding in the future. Storing the excess water somewhere in the city, as proposed by Van Roon (2007), Dietz and Clausen

(2008), and Howe et al. (2011), will probably be more effective. Also, the temperatures are expected to keep increasing in the future, which might cause more intense droughts during the summer months (IPCC, 2013). This is another argument for storing the water, because if stored, the water can be used again later if needed.

Another expected consequence of climate change is the sea level rise (IPCC, 2013). This might cause some additional troubles for the Netherlands, because a greater part of the country will become located below sea level. If a place is below sea level, it is difficult to drain the water away from there. However, it seems like the government is already thinking about this, since all the governmental reports that I examined suggested to create more space for water storage in the future (Ministerie van Verkeer en Waterstaat, 2000; Deltacommissie, 2008; Slomp, 2012; Ministerie van Veiligheid en Justitie, 2014; Rijkswaterstaat, 2016; Ruimtevoorderivier, 2016). Nevertheless, it will be a great challenge to obtain enough space for storing all excess water, caused by the combination of urbanization and climate change.

4.4 Conclusion

The general trend when changing a forested area into cultivated land seems to be an increase in surface runoff. When developing further into an urban area, the main idea is that the runoff increases even more due to additional impervious surface cover, with the largest increase in peak flow during summer. However, depending on climate and current urbanization level, the effects can be different or less abundant at certain locations.

Methods for reducing flood risks are becoming more sustainable, with solutions like increasing the infiltration capacity or storing the water in cities, instead of just making the water flow out of the city as quick as possible. Due to the expected increase in heavy rainfall events, water storage seems to be the best solution.

In the Netherlands, the government has been active in water management already since the 13th century. However, the view on which management techniques are the best started to change lately. Nowadays, the Dutch government is mainly focused on increasing the area of water storage. The main advice of researchers is to start cooperating between different stakeholders. But even though there is a great interest in new methods of water management, there has been so much investment in water protection in the past, that in many cases it is not cost-effective to change this.

For a better understanding of the impact of different urbanization levels, it would be good to have some research starting with 0% imperviousness and increasing to 100% imperviousness with small steps of for example 5 or 10%. In this way, you would not only see that with a higher level of urbanization the runoff increases, but also how much it increases with a certain amount of urbanization. This can then be used for city development. If you know exactly how much more runoff further development will cause, you can take measures for not letting it become a dangerous situation, or if there is no option to properly reduce the runoff you could decide not to develop the city further and therefore cause no unnecessary harm to the inhabitants of the area.

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