Science for Environment Policy
DG Environment News Alert Service

IN-DEPTH REPORT

Soil Sealing

March 2012

EUROPEAN COMMISSION

environment

Contents

Figures

Tables

Soil sealing: Introduction

Soils are a precious, non-renewable resource, the importance of which has been largely undervalued until recently.

Sealing soils with artificial, impenetrable surfaces interferes with the essential environmental, economic and social functions performed by soils. Services provided by soils include the provision of food and materials; the regulation of water, energy and matter; providing habitats to support biodiversity; the provision of spaces for recreational purposes; and the support of landscapes that have aesthetic and cultural values.

Driven by an increasing global population and a shift towards greater urbanisation, more natural land is being sealed by impervious surfaces: housing, transport infrastructure

and industrial and commercial development is being laid down over what was once open land. The impact of this development varies, depending on where the sealing occurs, the local conditions and climate, in addition to the size of the population and socio-economic conditions in the area.

This Science for Environment Policy In-depth Report explores research undertaken in the last few years related to the sealing of soils by artificial surfaces.

Part One examines the extent of the problem by looking at some of the reasons soil sealing occurs in urban areas, including the impacts of urban sprawl; covering open land with car parks; and paving over domestic gardens. Dealing with the growing expansion of sealed surfaces is challenging for all nations – some of the issues are listed for the cases of Germany and Austria.

Part Two explores the consequences on the water cycle of creating impervious surfaces on open land at the urban and watershed scales. The impacts of urban sprawl, paving domestic gardens and climate change on water quantity and quality is described through various case studies. In addition, some of the measures that can be taken to mitigate soil sealing on the water cycle are discussed, including management of drainage based on natural systems, the use of green roofs and harvesting rainwater in dry areas.

Part Three considers the impact of sealed land surfaces on city temperatures. Various case studies illustrate the impacts of land conversion on the heat island effect, including the social inequalities that can arise. Some of the ways to mitigate hotter temperatures in cities, as compared to the surrounding rural landscape, are explored. These include converting asphalt car parks to grass, the impacts of different methods of shading, including the use of photovoltaic cover, and the use of alternative cool materials in the construction of roads, pavements and buildings.

The consequences of soil sealing can be considerable and policies are needed to address the problems and minimise further impacts caused by the sealing of soils.

Part 1: The extent of soil sealing in urban areas

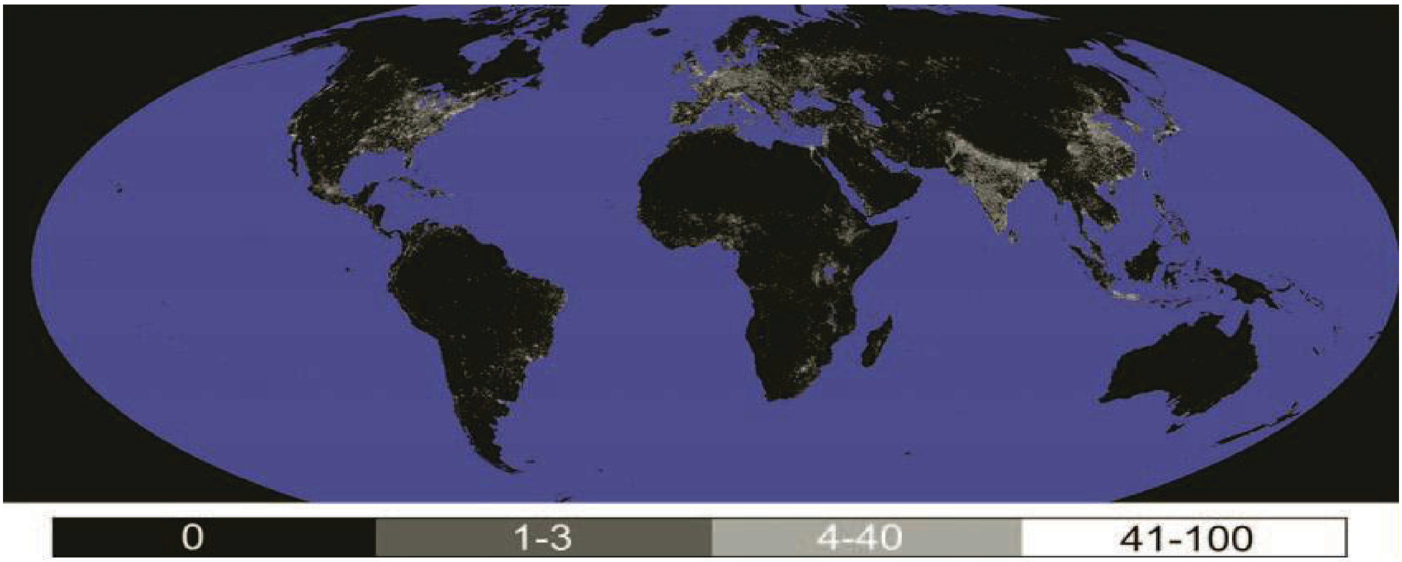


Figure 1. Satellite derived estimates of constructed area densities for 2000–2001 in a 1 square kilometre grid. The figure shows these values aggregated into four greyscale levels with percentage cover ranging from 0% to 100%

1.0 Introduction

In this section, the extent of soil sealing in urban areas is investigated. Urbanisation is a major reason why soil is overlaid with impervious surfaces: policymakers and urban planners need to understand and monitor the magnitude of the problem if appropriate and sustainable measures are to be put in place to curb the amount of open land that is being covered over in Europe and other parts of the world.

The increasing demand for land to house, transport and provide the social infrastructure for people living in cities is leading to greater urbanisation of previously rural areas. As a result, large areas of land are being covered in impenetrable or 'impervious' artificial surfaces, such as roads, buildings, pavements, driveways, car parks and airports, sealing off the soil beneath. Globally, it is thought that impervious surfaces cover 0.43% of the world's land area. This has been estimated by measuring the light emitted from the Earth's surface and is represented in Figure 1[1].

In many European countries, more than 10% of the land area has already been urbanised[3] and used for settlement and transportation, although not all of this urban land area has been sealed. The degree of soil sealing across Europe, for 2006, has been mapped by the European Environment Agency[2] (Figure 2).

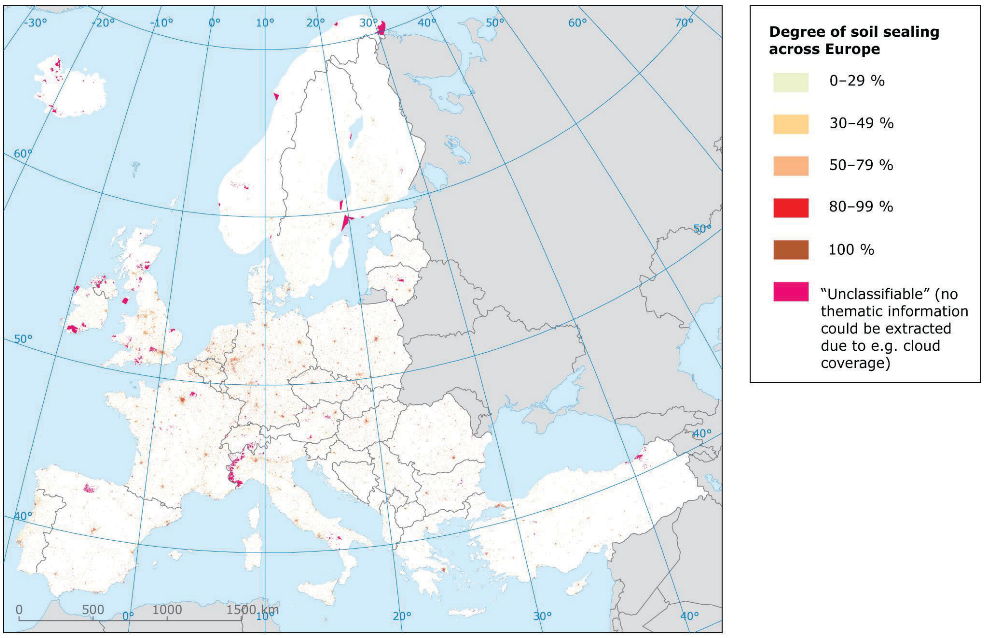


Figure 2. Degree of soil sealing across Europe

Figure 3 shows the degree of soil sealing as a percentage of the total land area for individual European countries in 2065[3].

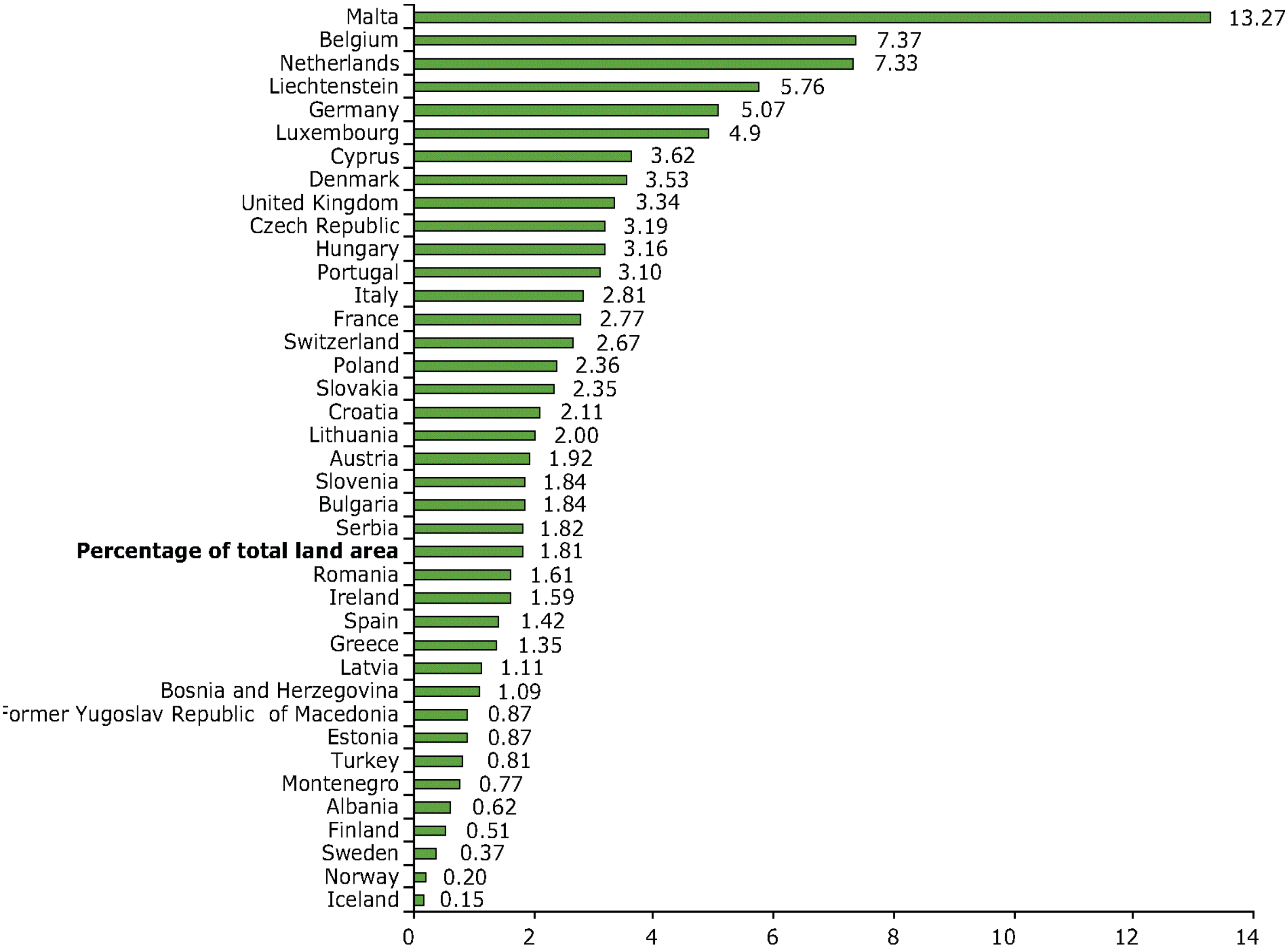


Figure 3. Degree of soil sealing as a percentage of total land area, in European countries (Eurospean Environment Agency 2006[3])

Sources:

1. Sutton, P.C., Anderson, S.J., Elvidge, C.D. (2009) Paving the planet: impervious surface as proxy measure of the human ecological footprint. *Progress in Physical Geography*. 33: 510-527.

2. Map accessed from European Environment Agency: http://www.eea.europa.eu/data-and-maps/data/eea-fast-track-service-precursor-on-land-monitoring-degree-of-soil-sealing-100m-1

3. Chart accessed from European Environment Agency: http://www.eea.europa.eu/data-and-maps/data/eea-fast-track-service-precursor-on-land-monitoring-degree-of-soil-sealing-100m-1

1.1 The extent of urban sprawl

Urban sprawl is defined as a low-density and land-consuming urban expansion. In many European cities, an expanding, or rapidly changing population, growing affluence and dependency on motor vehicles has led to sprawling development. Urban sprawl is a significant cause of soil sealing in suburban areas. Cities are changing shape and becoming spread out rather than retaining the compact nature that has previously characterised many urban settlements in Europe.

Low density development takes place at the periphery of the city edges. Whilst there can be economic benefits (e.g. investment in new industrial and commercial hubs) and social benefits (e.g. less crowded living and close proximity to the countryside), this has led to an increase in the construction of impervious surfaces on what was once rural land. As rural land is typically associated with open green spaces and agricultural use and urban land use is associated with housing, industry, commerce and transport infrastructures, this has implications for the environment as natural landscapes are absorbed into urban areas and open ground is sealed.

In Germany, for example, land has been 'consumed' or converted to urban use at a rate of 80-130 hectares a day between 1993 and 2004, so that by 2007, 12.8% of land in Germany was being used for settlement and transport purposes, compared with 7.1% of the land area in 1950. In other densely populated European countries, such as the Netherlands, the urbanised share of land is 18% and in Belgium, 14% of the land has been urbanised[1].

The growing spread of impervious surfaces is harmful to the environment and reduces the ability of ecosystem services to provide the level of support people rely on, such as food production, the supply of clean water, climate and energy regulation and the provision of a variety of habitats for biodiversity to thrive.

Sources:

1. Nuissl, H., Haase, D., Lanzendorf, M., Wittmer, H. (2009) Environmental impact assessment of urban land use transitions - A context-sensitive approach. *Land Use Policy.* 26: 414-424.

Key points regarding the spread of sealed surfaces in urban areas

In terms of land use change, major challenges continue to be:

- The conversion of virgin, arable and forest land into the urban in the periurban areas (the periurban is the area around urban settlements which blends into the rural landscape) around the core of cities[2].
- The conversion of virgin, arable or forest land into transportation areas (roads, motorways, airports)[2].
- In periurban areas of Europe, the use of open land for bioenergy crops or other types of urban/hobby farming[2].

In response, policymakers and planners should:

- Improve the quality of life in cities[1].
- Consider urban planning enforcement as the key point to manage urban sprawl[3].
- Support municipalities to use fallow land (e.g. to tear down unoccupied real estate property to ensure new urban open space or to modernise old buildings)[1].
- Exhaust existing potential of land usage to stop increased land use for new settlements especially on the urban outskirts[1].
- Use urban models like 'compact city' with the goal of increasing the urban density in cities[1].
- Improve the mixed use of land (living and working, shopping and cultural services) in urban green planning in the cities to stop the process of suburbanisation, which increases the demand for land. Government funding is necessary[1].
- In shrinking cities turn unused housing and industrial sites into brownfields (enabling land to be partially desealed)[2].

Sources:

1. Artmann, M. (2011) Personal correspondence
2. Haase, D. (2011) Personal correspondence
3. Munafo, M. (2011) Personal correspondence

Urban growth and the consequences for soil sealing

In urban areas where the population is increasing, greater demands will be made on natural resources, including land for building homes and industrial, commercial and transport infrastructures. In addition to meeting these needs, the desire to move out of city centres to the suburbs drives the development of urban sprawl.

Soil sealing driven by urban sprawl is characteristic of many cities today. For example, in some Mediterranean urban areas, cities have become less compact as the population spreads outwards from the city centre. In this process, populations become less dense; the rural fringes of the city change shape and become fragmented as patches of farm land are converted to urban occupation accommodating housing, industry and related infrastructures.

Two case studies presented here illustrate the problem of urban sprawl: Case Study 1 (page 8) for Rome, and Case Study 2 (page 9) for Leipzig. These demonstrate that the process of the growth of impervious surfaces in urban areas is not a uniform and predictable process. Local conditions and economic and social changes have specific impacts on different cities and regions. Nevertheless, understanding how and why these changes in land cover happen will help land planners and policymakers make informed decisions about using the most appropriate measures to contain the spreading cover of impervious surfaces in urban areas.

Case study 1: Urban sprawl in Rome, Italy

A survey of changes to land use and soil sealing across 1,477 sites in the municipality of Rome covering the period 1949 to 2006 revealed interesting patterns of urban change[1]. As can be seen from the maps in Figure 4, which shows changes in the amount of sealed surface areas, Rome grew from being a compact city in the 1940s to one demonstrating the effects of urban sprawl by 2006.

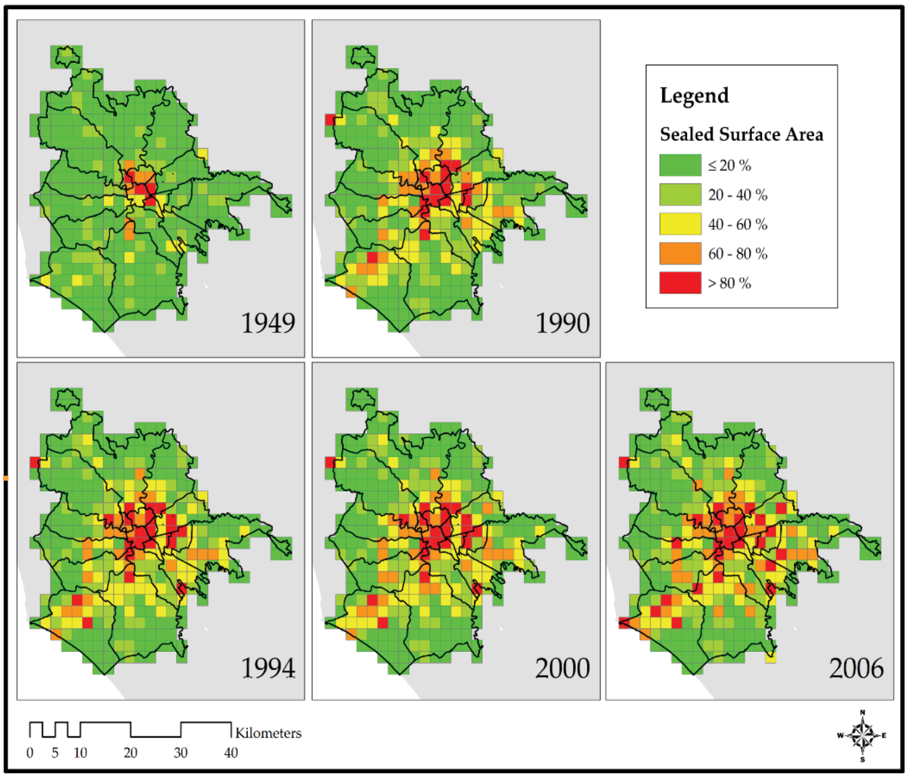


Figure 4. Trends of soil sealing in Rome (1949-2006)

The number of sites that have been sealed increased from 117 in 1949 to 388 in 2006, with a corresponding increase in the surface area that has been sealed: from 8% in 1949 to over 26% of the city in 2006, a three-fold increase. Over this time, sealed areas have developed further from the city centre.

During the 130 years between 1870 and 2001, the resident population grew ten times over. From the 1950s to the 1970s, population growth and the amount of soil that was sealed grew at a similar rate (Figure 4). However, from the 1970s through to 2006, the population stabilised and then fell while the rate of soil sealing continued at the same pace. The decoupling of population growth from soil sealing rates was due to urban sprawl, driven mainly by speculation in the housing sector. In effect, the amount of soil sealed per person has doubled over a 50 year period, even though the population has started to decline.

Land protection measures to contain soil

sealing have not been entirely successful: for example, sealed sites in protected areas increased by 56% from 1949 to 2006. This compares with an increase of 71% outside protected areas over the same time period. It remains to be seen whether new legislation, enacted in 2008, aimed at curbing the spread of impervious cover and protecting green spaces, will be effective in reducing the amount of soil sealed in urban areas.

Source:
1. Munafò, M., Norero, C., Sabbi, A. and Salvati, L. (2010) Soil Sealing in the Growing City: A Survey in Rome, Italy. *Scottish Geographical Journal*. 126:153-161.

Case study 2: Long-term trends in land use change, Leipzig, Germany

The impact of a country's social, cultural and economic circumstances can have profound consequences for the development of urban areas, including the amount of impervious cover found in cities. These impacts are clearly demonstrated by a study[1] which followed the long-term trends of change in land use in the city of Leipzig, Germany. Until recently, Leipzig had actually become less urbanised over the past few decades.

Major trends occurred during this time, caused by the effects of two world wars, socialist rule and a move to a market economy. Other western cities face similar social and economic issues. Rapid industrialisation caused dynamic growth between 1870 and 1930, making Leipzig the fourth largest city in Germany.

The city reached its maximum population of 700,000 in the early 1930s with expansion of the urban area around the city centre. In step with this growth, the percentage of impervious cover expanded from less than 7% in 1870 to 17% in 1940.

The growth of impervious surfaces in urban areas is not a uniform and predictable process, as this Leipzig case study and the Rome case study (no.1) demonstrate. Local conditions and economic and social changes have specific impacts on different cities and regions.

Nevertheless, understanding how and why these changes in land cover happen will help land planners and policymakers make informed decisions about using the most appropriate measures to contain the spreading cover of impervious surfaces in urban areas. Under socialist rule after the end of the Second World War in 1945, expansion of Leipzig stopped. The focus was on city centres and the process of suburbanisation and consequently, urban sprawl almost ceased.

In the post-socialist era after 1989, there was again rapid expansion at the edges of the city into the surrounding suburban towns and villages, driven by housing, industrial, shopping and other commercial developments. This development was low-density: the concentration of inhabitants in the city dropped from more than 3500 people per square kilometre in 1990 to less than 1700 people per square kilometre in 2006, while the amount of residential land increased from 2500 hectares in 1989 to 2730 hectares in 2006. This trend has since been reversed: by the late

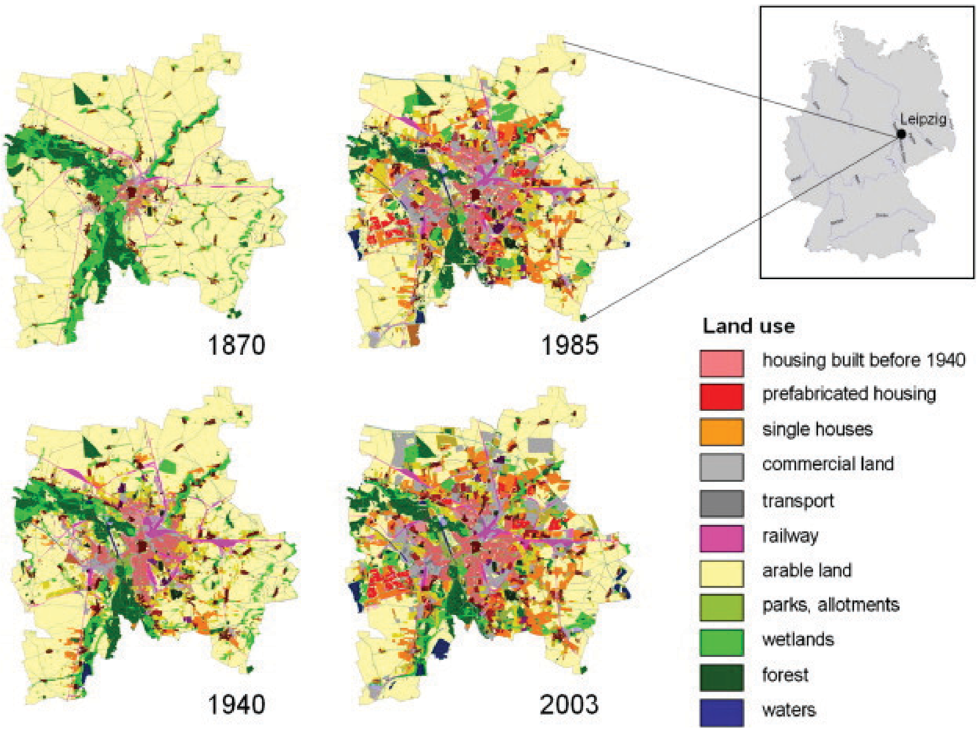


Figure 5. Land use change in the city of Leipzig between 1870 and 2003. The first phase of growth occurred after 1870 representing the industrialisation and transport development until World War II.

1990s, falling industrial production and birth rates, alongside a massive translocation of people from eastern Germany to the western part of the country, has seen a marked reduction in urban sprawl. Today Leipzig's population has fallen to half a million, although since 2000, there are signs of growing urbanisation once again. A broad picture has emerged. The evolving transformations that have been taking place in Leipzig illustrate the contradictory processes that occur during the historical development of a city. Although major trends can be seen, there have been instances of growth and degeneration, densification and de-densification, ageing and rebirth. Knowing that developments in cities can be patchy and changeable will help urban planners understand such processes and allow realistic sustainable development plans to be drawn up.

Sources:

1. Haase, D and Nuissl, H. (2010). The urban-to-rural gradient of land use change and impervious cover: a long-term trajectory for the city of Leipzig. *Journal of Land Use Science.* 2: 123-141.

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

1.2 Car parks

One of the problems associated with urban sprawl is the increased reliance on private motor vehicles for transport. Where to park all the additional cars creates further demand for land.

Land dedicated to the use of motor vehicles contributes to the growing footprint of sealed land surfaces in urban areas, with major environmental consequences. For example, paving over land to create car parks increases the risk of flooding by causing significant amounts of rainfall to run off the impervious surfaces. Water cannot percolate through the sealed surfaces and is lost to underground water systems. Run-off can overload drainage systems, concentrate pollutants and reduce water quality when discharged into water courses or require costly treatment before being released into waterways. In addition, car parks encourage the use of private vehicles, and less use of public transport, which increases traffic pollution in the area. Car parks are especially associated with the phenomenon of urban sprawl.

Case study 3: Car parks in Tippecanoe County, USA

The use of vehicles is projected to increase worldwide in the coming years. Although the intensive use of private motor vehicles in the US is well recognised, countries in Europe are also expected to see a rise in the numbers of vehicles on the road. For example, Germany is expected to see vehicle ownership increase by 0.6%, from 48 million in 2002 to 57 million vehicles in 2030; France, a 1.3% increase, from 35 million to 50 million vehicles by 2030; and Great Britain, a 1.3% increase, from 31 to 44 million vehicles by 2030[1].

Large areas of land are sealed by paved parking areas, which are typically found at schools, commercial and industrial complexes, hospitals, places of religious worship and housing estates. Two recent US studies[2,3] have highlighted how much land is needed to park vehicles in car parks.

Car parks in Tippecanoe County, Indiana, in the Midwest United States, were found to cover 5.65km^2 of land, accounting for 0.44% of the county area and 6.57% of the urban cover in the county. Land dedicated to car parks was, on average, 20% greater than the land covered by the buildings they are attached to. Car parks in the urban areas covered three times more land than was covered by urban parks. The study estimated there were 202,714 parking spaces in the county. For every person of driving age there are around 1.7 parking spaces available and for every registered passenger vehicle, 2.2 spaces are available for parking the vehicle. To put this in perspective, the researchers say:

> *"If all of the vehicles in the county were removed from garages, driveways, and all of the roads and residential streets and they were parked in parking lots at the same time, there would still be 83,000 unused spaces throughout the county."*

In one urban district, of all the land covered by buildings and parking lots, 55% of the land is occupied by car parks and 45% is occupied by buildings.

The environmental impacts from the extensive coverage of car parks are considerable. For Tippecanoe County, the overall value of lost environmental services provided by land covered with car parking was estimated to be US$22.5 million (assuming all the county's land covered by car parks was converted to wetlands). In addition, run-off of water increases by 900%, compared with the use of the land prior to being converted into car parks. Associated with this is the increase in pollutants, such as heavy metals, oils and greases, suspended solids and nitrogen and phosphorus. The expansion of car

parks was linked to urban sprawl in the US studies, which suggest that there are ways to reduce the need for such extensive areas of car parks and their environmental impacts. For example:

- **Promote** shared parking practices between businesses
- **Convert** parts of unused car parks to green spaces
- **Change** 'zoning' laws to promote a greater mix of residential and commercial use. This would encourage the expansion of public transport and reduce the need for car parks.
- **Use** greener alternatives, such as permeable paving, or add green roofs above car parks where possible.
- **Consider** how car parks can be integrated into sustainable urban drainage systems, such as using permeable surfaces.
- **Consider** new car parks in the regional context, not just at the local scale: a 'think regionally, act locally' approach.
- **Consider** capping the maximum as well as the minimum number of parking spaces required with planning applications for new developments. The amount of parking available for new businesses could be reduced, for example, provided there is access to shared car parks nearby.

Sources:

1. Dargay, J., Gately, D. and Sommer, M. (2007) Vehicle Ownership and Income Growth, Worldwide: 1960-2030. *Energy Journal*. 28:143-170. Additional resource (researcher presentation): http://www.usaee.org/USAEE2006/papers/dermotgately.pdf

2. Davis, A.Y., Pijanowski, B.C., Robinson, K., Engel, B. (2010) The environmental and economic costs of sprawling parking lots in the United States. *Land Use Policy*. 27: 255–261.

3. Davis, A. Y., Pijanowskia, B. C., Robinson, K. D., Kidwell, P. B. (2010) Estimating parking lot footprints in the Upper Great Lakes Region of the USA. *Landscape and Urban Planning*. 96: 68–77.

1.3 Paved gardens

People want to choose how they design their gardens. But small changes householders make to their gardens over an extended period of time can add up to major environmental impacts. Gradually adding more paved areas to gardens increases the risk of urban flooding: rainfall cannot seep into the ground and instead, water runs off the paved surfaces into storm water and sewage systems. Climate change is likely to increase the intensity and frequency of heavy rainfall events and urban drainage systems could be overwhelmed, causing flooding.

Case study 4: Paved gardens in Flanders, Belgium

One study[1] has examined how the impact and extent of paved areas in domestic gardens has changed over time in five residential areas in the Leuven municipality of Flanders, Belgium.

The Flanders region is highly urbanised: the built-up area covers 13.8% of the land and has increased in size by 50% between 1985 and 2005. 73% of the houses have gardens which collectively cover 8.3% of the total built-up area.

Houses in the study area were built as social housing schemes between 1923 and 1962, but are now privately owned.

When the houses were originally built, the building plans allowed for 38% of the total garden area to be paved over. But by 2008, around 56% of the neighbourhood gardens were paved. There was more paving in high density housing areas (73%) than in low density housing areas (39% paved surfaces).

Much of the new paving was in front gardens and to create driveways. One consequence of this is that large impervious areas are connected together across neighbourhoods, increasing the risk of overflowing sewers and potential urban flooding.

Ways to make the paved footprint in front gardens smaller include:

- only paving two narrow strips for tyre tracks
- using permeable types of paving (e.g. paving blocks with soil or sand between the joints).

Individual choices that householders have been able to make about their own gardens in these housing estates have had a large collective impact on the amount of urban land that has been covered with sealed surfaces. Government policies originally designed to guide social development have gradually been replaced by individual choice. The researchers state:

> *"These numbers should make public and policymaker more aware of the power and "tyranny of small decisions" (Goddard et al., 2009[2]) and the potential environmental implications that come with them."*

Suggestions for curbing excessive garden paving

Residents should be encouraged to have a green front garden, as there are a number of benefits:

- unsealed surfaces allow water to filter into the ground, preventing excessive rainfall run-off
- garden plants remove carbon dioxide traffic pollution
- green areas provide refuges for biodiversity
- green gardens improve the aesthetics of the neighbourhood – in addition to a pleasing appearance, having trees and other plants help reduce noise, wind and dust
- shade from garden plants cool the area so less energy is needed for fans or air conditioning in hot weather

Sources:

1. 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 Plannin*g. 100: 57-66.

2. Goddard, M.A., Dougil, A.J., Benton, T.G. (2009). Scaling up from gardens: biodiversity conservation in urban environments. *Trends in Ecology and Evolution*. 25: 90-98.

Case study 5: What is being done? Examples from Germany and Austria

Although European nations recognise there is a problem with the amount of rural land being converted to urban use, and the corresponding increase in the amount of soil sealing, targets to control land conversion have proved difficult to meet.

For example, in Germany there are quantity and quality goals regarding sustainable land use. The quantity goal aims to reduce land use to 30 hectares/day until 2020 regarding land for settlement and traffic. The quality goal aims to promote inner-development to outer-development in a ratio of 3:1[1]. There is a wide acceptance (by scientists, planners and politicians) for the need of such goals but it will be hard to reach them. Between 2006 and 2009 the land use for traffic and settlement amounted to 93 hectares per day, and 50% of this land was sealed[2]. The federal government demands that a mixture of several instruments have to be developed and put into practice[3,4,5]:

1. Economic fiscal measures[6,7,8] (e.g. fee for rezoning land, land tax, Split-wastewater-fee)
2. Informational instruments[9,10] (e.g. fallow land register, register for gaps between buildings)
3. Planning law instruments[11,12,13,14,15,16] (e.g. tradable certificates for developed areas, regulation of soil sealing with quantity-forcing through orientation values for housing development etc.)

For example, in some German federal states such as Hesse and Baden-Wuerttemberg, wastewater bills are calculated according to the Split-wastewater-fee. This separates the costs associated with wastewater disposal into sewage systems based on drinking water consumption, from wastewater disposal associated with rainfall run-off from sealed surfaces[17].

In Austria it is already clear that the local sustainability goal has not been achieved. Soil sealing should be reduced to 1 hectare a day until 2010, but still 8 hectares a day between 2007 and 2009 were sealed[18]. The Austrian Urban Planning Conference suggests quantity forcing for zoning building land at the municipal and national level as well as promotion of inner development through the reuse of industrial and commercial brownfield sites by economic incentive systems[19].

Both Austria and Germany see a need to improve the cooperation between federal, state and local authorities, especially the municipalities that are responsible for implementing appropriate measures in practice to reduce soil sealing.

Sources:

1. Umweltbundesamt (ed.) (2003): Reduzierung der Flächeninanspruchnahme durch Siedlung und Verkehr - Materialienband – Berlin. www.umweltdaten.de/publikationen/fpdf-l/2587.pdf (04.04.11)
2. Umweltbundesamt (2010): Information 26. Oktober 2010. Zunahme der Siedlungs- und Verkehrsflächen vom Jahr 1993 bis zum Jahr 2009. http://www.umweltbundesamt.de/rup/veroeffentlichungen/zunahme.pdf (12.04.2011)
3. Arlt, G.; Richter, U.; Weise P. (2001): Flächennutzungskonkurrenzen in Großstadtregionen – Ausgangsbedingungen und Grundlagen der Analyse, Bewertung und Instrumentierung. In: Richter, U.; Weise, P.; Biehler, H. (eds.): Nachhaltige Siedlung- und Flächenentwicklung in Großstadtregionen. Entwürfe für ökologisch-ökonomische Gestaltung, Instrumentierung und Organisation urbaner Systeme. Stadtökologie Band 4, Berlin: 17-84.
4. Birkmann, J. (2004): Monitoring und Controlling einer nachhaltigen Raumentwicklung. Indikatoren als Werkszeug im Planungsprozess. REGIO spezial Band 2, Dortmund.

5. Flacke, J. (2003): Mehr Stadt – Weniger Fläche. Informationssystem nachhaltige Flächennutzung. Ein Instrument zur Förderung einer nachhaltigen Siedlungsentwicklung, Flensburg.
6. Jörissen, J. & R. Coenen (2004): Instrumente zur Steuerung der Flächennutzung. Auswertung einer Befragung der interessierten und betroffenen Akteure. Büro für Technikfolgen-Abschätzung beim Deutschen Bundestag, Hintergrundpapier Nr. 10.
7. Breuste, J. (2001): Nachhaltige Flächennutzung durch den Einsatz mengen- bzw. preissteuerndernstrumente. In: Zeitschrift für Angewandte Umweltforschung (ZAU), 14:1-4: 360 – 369.
8. Dollinger, F., Dosch, F. & B. Schultz (2009): Fatale Ähnlichkeiten? Siedlungsflächenentwicklung und Steuerungsinstrumente in Österreich, Deutschland und der Schweiz. In: Wissenschaft & Umwelt, interdisziplinär: 12: 105 – 125.
9. Dinkelberg, W., Lantzsch, P. & U. Moka (2001): Entsiegelungsflächen-KatasteralsInstrumentfüreineffektives Flächenressourcen-Management. In: Marktredwitzer Bodenschutztage Tagungsband 2 „Umsetzung der Bodenschutzgesetze und Flächenressourcen-Management": 23-28. www.bmvbs.de/-,302.980267/Pressemitteilung.htm (13.08.10)
10. Müller-Herbers, S.; Molder, F.; Kauertz, C. (2011): Innenentwicklungskataster als Entscheidungsgrundlage für die kommunale Planung. In: Bock, S.; Hinzen, A.; Libbe, J. (eds.): Nachhaltiges Flächenmanagement – Ein Handbuch für die Praxis. Ergebnisse aus der REFINA-Forschung, Berlin.
11. Léon, D. C. (2005): Der Vorschlag des Nachhaltigkeitsbeirats Baden-Württemberg zur Einführung eines Systems handelbarer Flächenzertifikate in Baden-Württemberg. In: Informationen zur Raumentwicklung, Heft 4/5.2005. 267-271.
12. Der Rat von Sachverständigen für Umweltfragen (2004): Umweltgutachten 2004. Umweltpolitische Handlungsfähigkeit sichern. Baden-Baden.
13. Bahlburg, C.H. & U. Rühl (2005): Mengenvorgaben im Raumordnungsplänen. Methoden und Erfahrungen aus Berlin Brandenburg. In: Informationen zur Raumentwicklung. Heft 4/5.2005: 205-210.
14. Bundesamt für Bauwesen und Raumordnung (2008): Fläche im Kreis. Ergebnisse des ExWoSt-Forschungsfelds "Kreislaufwirtschaft in der städtischen/ stadtregionalen Flächennutzung" - "Fläche im Kreis" www.flaeche-im-kreis.de/ergebnisse/
15. Örok, Österreichische Raumordungskonferenz (ed.) (2009): Räumliche Entwicklungen in österreichischen Stadtregionen. Handlungsbedarf und Steuerungsmöglichkeiten. Schriftenreihe Nr. 179. Wien: Eigenverlag.
16. Landschaftsinitiative, Raum Für Mensch und Natur (2010): Landschaftsinitiative: Bundesrat wandelt ohne klares Ziel. Pressemitteilung , 21. Januar 2010. Basel.
17. Breuste, J.H. (2009) The Urban Grey: Soil sealing key indicator for urban ecological functionality and ecological Planning. See: http://www.stadtoekologie-berlin.de/en/upload/_aktuell/Session1_Breuste.pdf
18. Bundesministerium Für Land-Forstwirtschaft, Unwelt und Wasserwirtschaft (ed.) (2009): Indikatoren-Bericht zur Biodiversität in Österreich. Wien: Eigenverlag.
19. ÖROK, Österreichische Raumordnungskonferenz (2010): Österreichisches Raumentwicklungskonzept 2011. Arbeitspapier der AG III „Umwelt – Klimawandel – Ressourcen", Graz.

Gaps in resources identified by researchers to address soil sealing in urban areas

- Lack of an EU framework and national legislations on soil sealing.
- Lack of coordination between government departments that deal with planning and investment
- Inadequate planning systems that do not integrate infrastructure development across administrative boundaries
- Local and regional tax and re-investment systems often favour development that leads to urban sprawl, for example, by creating competition between municipalities for tax revenues.
- Missing data on soil sealing and no standardised methodology to monitor soil sealing
- Lack of local resources to address problems
- Insufficient political will to implement policy measures that address the issue of soil sealing in urban areas

Sources:

1. Ravetz, J., Piorr, A., Tosics, I. (eds) (2010) Rural – Urban Regions and Peri-urbanisation in Europe: Towards a European Policy to Sustain Urban-Rural Futures. (2010) The report can be accessed from: http://www.plurel.net/images/Peri_Urbanisation_in_Europe_printversion.pdf
2. Artmann, M. (2011) Personal correspondence
3. Dagmaar Haase, D. (2011) Personal correspondence
4. Munafo, M. (2011) Personal correspondence

The extent of soil sealing: recommendations for policymakers

- Data for the extent of soil sealing should be improved and not just estimated. It is also important to use comparable data and standardised methodologies to monitor soil sealing phenomena, at least in every country.
- There is considerable competitive pressure between the municipalities in some European countries and they are forced to create new settlement and industrial areas. In addition, shrinking cities do not use fallow land but designate new building areas. To reduce the pressure on local authorities, intercommunity and regional cooperation would be beneficial.
- Goals to reduce soil sealing and land use should be defined on a regional level. Local strategies should define how to reach the goals: therefore federal states and municipalities are responsible for implementing appropriate measures in practice.
- Support local farmers so that they continue farming in the periurban area and not sell their land to developers. This could be done by implementing green banks.
- Apply the concept of ecosystem services to urban regions to find out the most valuable areas (e.g. where sealing of soils is unavoidable, use land with a low organic function).
- Better assess the value of open land and soil as a resource by planners and thus influence policymakers to 'sell' the soil in their urban region to developers.
- Set up an urban conservation agenda for natural resources and ecosystems.
- Promote multifunctional land use to create win-win situation for nature and society.
- Promote sustainable land use management by using water permeable coverings where possible.
- Increase the amenity value of sealed surfaces, e.g. covering buildings with green roofs.

Sources:
1. Artmann, M. (2011) Personal correspondence
2. Dagmar Haase, D. (2011) Personal correspondence
3. Munafo, M. (2011) Personal correspondence

Part 2: Soil sealing and the urban water cycle

2.0 Introduction

This section of the report highlights the impacts of sealed surfaces in urban areas on the water cycle and some of the responses that can be taken to reduce these impacts.

Some of the rain that falls on open ground infiltrates the soil; some evaporates back into the atmosphere; and some runs off natural surfaces, eventually reaching streams, rivers, lakes and the oceans. When natural cover is sealed over with impenetrable surfaces, through residential, commercial and industrial development, such as paving for car parks and gardens, and transport infrastructure including roads and airports, there is a significant impact on natural water systems. Sufficiently high areas of impervious cover in urban areas affect the water balance and water regulation at local and watershed scales.

For example, increased impervious cover typically causes higher and faster flows of surface water run-off, especially during high precipitation (e.g. rainfall) events. Streamflow volumes and stream peak flow rates are increased by concentrated surface water run-off that enters streams and rivers either directly or from wastewater treatment plants that collect run-off from conventional stormwater drains and underground pipes.

The likelihood of floods also increases. Environmental damage can result from physical impacts of increased and faster water flows, from greater amounts of sediments and urban pollutants washed into streams and warmer run-off waters. These affect the quality and quantity of receiving waters.

In addition, increased surface run-off reduces available water for evaporation, which would otherwise have a strong cooling effect in urban areas. Frequently, less water infiltrates the soil to replenish groundwater supplies. Recharging groundwater is essential to maintain the base flow of streams and to feed springs that maintain wetlands.

Urban water cycle: Key points

- Soil sealing increases peak discharge rate, total run-off volume and stream flashiness (streamflow response to storms – typically rising and falling quickly). Soil sealing also contributes to the heat island effect that increases stream temperature[1].
- It is important to keep as many areas open and unsealed in urban areas environments as possible; but also to pay attention to pedestrian areas, which should be safe and accessible by foot under/after heavy rainfall[2].
- If surfaces do need to be sealed, it is better to use forms of 'semi-sealing', which provide better kf-values (infiltration capacity) than 100% surfaced areas[2].
- It is important to initiate and support the ecological restoration of inner-urban brownfields and convert them - even temporarily - into urban greenspace and recreation areas[2].
- Open (unsealed) surfaces enhance sensitive flows of evapotranspiration - thus they also improve the health of urban dwellers by increasing cooling [2].
- Much small-scale sealing takes place undetected by authorities but the accumulated impacts can be significant[3].
- The greatest impacts of sealing occur where underlying soils are highly permeable[3].
- There are many enviro-friendly paving products on the market[3].
- The key issues are to understand 1.) urban evaporation and 2.) the link between the water balance and the urban climate increasing evaporation and infiltration in urban areas[4].

1. Li, M-H (2011) Personal correspondence.
2. Haase, D. (2011) Personal correspondence.
3. Nawaz, R. (2011) Personal correspondence.
4. Hamdi, R. (2011) Personal correspondence.

2.1 Urban sprawl and the water cycle

Changes in land use from natural, rural and agricultural purposes to urban uses typically increase sealed surfaces. In particular, urban sprawl or developments at the edges of cities covers natural landscapes with urban infrastructure affecting the water balance of the area. All urban development, however, has an impact on the water balance: over the city scale the long-term accumulated impacts can be significant.

Case study 6: Urban sprawl in Leipzig, Germany

Two studies in Leipzig, Germany[1,2], have examined how urban sprawl has affected long-term changes in the city's water balance . One of the studies examined the response of various authorities and the civil population to this significant environmental impact.

Water balance is affected by the amount of water that runs off surfaces, the amount of water that is lost by evapotranspiration to the atmosphere and by the amount of water that seeps through the soil and is retained there or percolates through to groundwater systems. Covering natural areas land surfaces with impervious cover interferes with these processes and so affects the natural water balance.

Both these studies complement the Case Study no.2 (land use change in Leipzig) in Chapter One of this report. Impervious cover increased in Leipzig by 19% between 1945 and 2003, driven at first by socialist development of industry and large housing estates, and then later by residential development (which contains 40-60% impervious cover) and industrial and commercial development (with around 80-100% impervious cover), especially after 1990.

The researchers compared the water balance in the Leipzig area from 1870 to 2003. Overall, the impact of urban development on the water balance from 1870 to 2003 increased direct run-off rates by 282% in the area; evapotranspiration rates decreased by an average of 25% and groundwater recharge decreased by 4% over the same time (see Figs 6, 7, and 8).

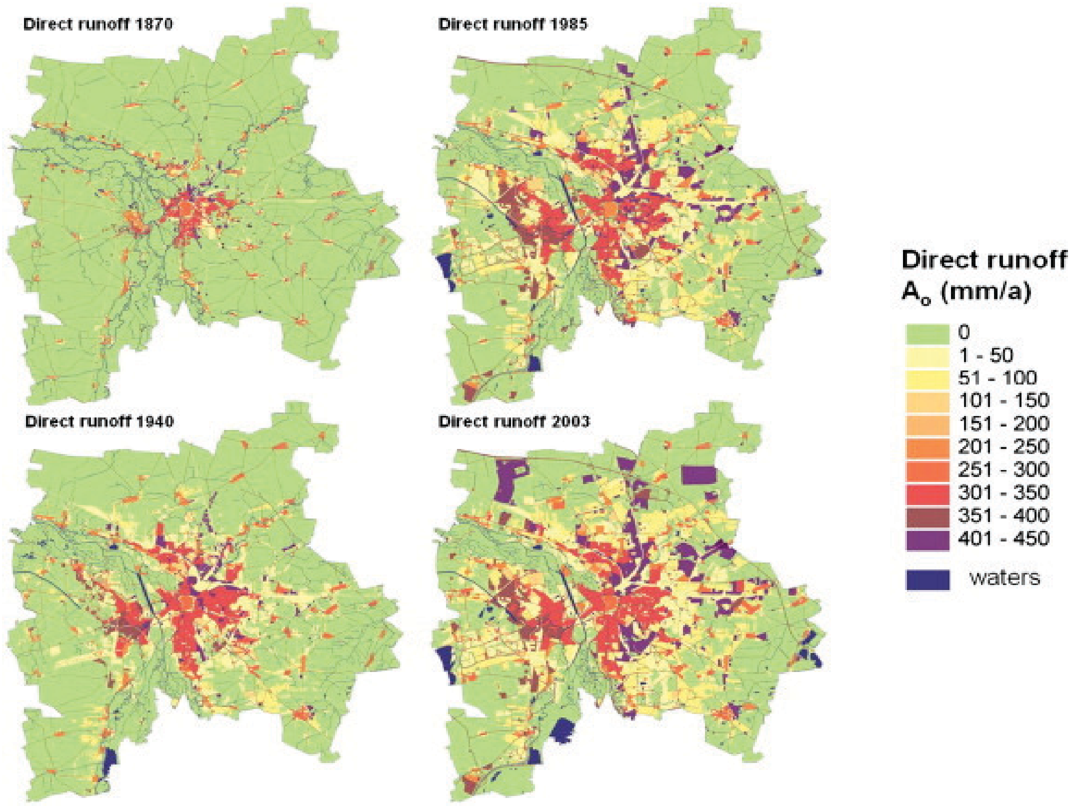


Figure 6. Mean annual direct run-off rates in Leipzig for the 4 time slots 1870, 1940, 1985 and 2003.

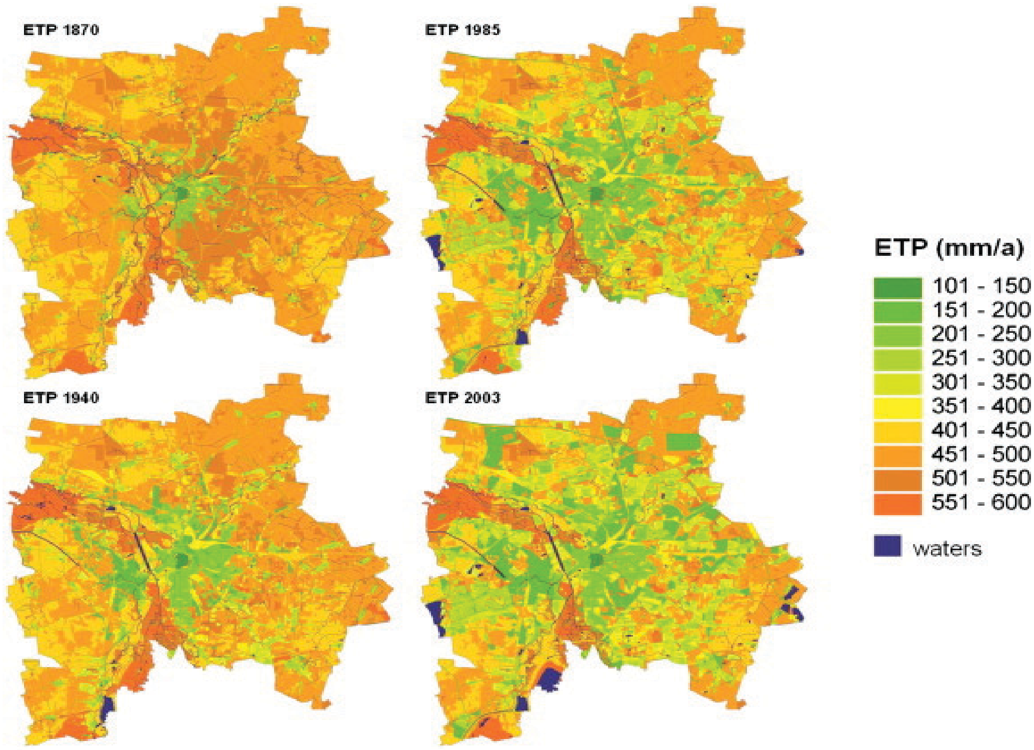


Figure 7. Mean annual evapotranspiration in Leipzig for the 4 time slots 1870, 1940, 1985 and 2003.

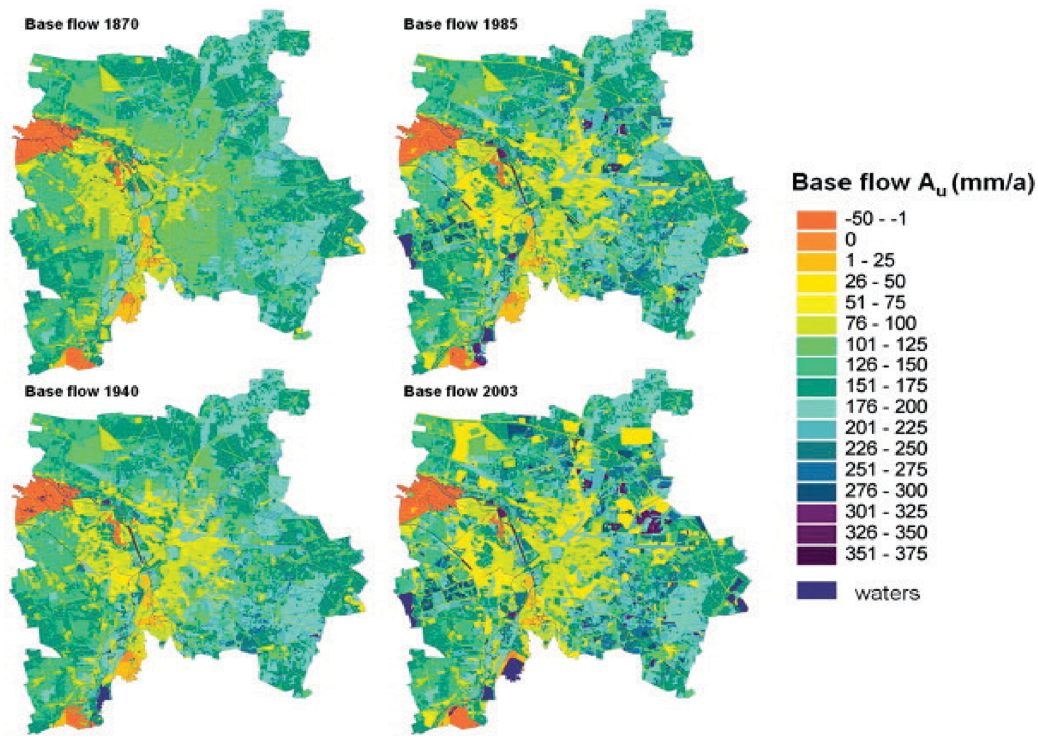


Figure 8. Mean annual base flow Au (representing the groundwater recharge rates) in Leipzig for the 4 time slots 1870, 1940, 1985 and 2003.

Proportion of impervious land (%)	Area (ha)	Evapotranspiration (mm/a)	Surface run-off (mm/a)	Seepage water rate (mm/a)
>0–20	1111	351–550	1–150	51–300
>20–40	626	251–450	51–250	51–250
>40–60	2547	201–350	151–300	101–200
>60–80	146	151–300	251–350	51–125
>80–100	1842	151–200	351–450	1–75

Table 1: Water balance of the newly sealed areas in Leipzig since 1940

Average yearly precipitation for the area is around 570mm: comparing the run-off rate for different levels of impervious cover, the study found that the uncovered soils (which were loess-type soils) have annual average run-off rates of around 25-150mm. Since 1940, run-off for the area has increased significantly. For example, with between 40 and 60% impervious cover (e.g. in pre-fabricated housing estates) the increase in run-off is up to 200mm a year higher than the average precipitation amount (see Table 1). In areas with the highest impervious cover (80-100% sealing), direct run-off has increased by 450mm a year, which is more than 75% of the average annual precipitation.

The areas with the highest sealing rates were associated with commercial developments, the new airport and transport infrastructure. In particular, residential and commercial development after 1990 was responsible for high rates of soil sealing.

In addition, the evapotranspiration rates decreased as surface run-off increased – (see Table 1 and Fig. 7). For example, with less than 20% and up to 40% impervious cover, evapotranspiration rates decrease by 100-150mm a year: this compares with a decrease in evapotranspiration of 450mm a year where impervious surfaces cover 80 to 100% of the land surface.

Although seepage rates have fallen significantly, replenishment of groundwater is estimated to have fallen by 4% between 1870 and 2003 (compared with 1870 levels). Groundwater recharge has declined in some areas, but increased in others (see Fig. 8). Areas of good infiltration capacity which are affected by increased surface run-off, experience groundwater recharge increases. This is not so much as an effect of land use change at the respective locations, but as a neighbourhood effect.

Overall, this implies that the water balance has shifted towards greater surface run-off, less retention of water in the soils and less underground storage of water. Low-lying areas are already affected by periodic flooding after heavy rainfall and greater urbanisation and sprawl could exacerbate this problem.

The studies suggest that accumulated urban sprawl, rather than short-term changes, has had a significant long-term impact on Leipzig's water balance.

Socio-economic considerations

In order to understand how different sectors of society perceive the environmental impacts of urban sprawl, particularly on the water balance, the change in water balance was explored within the DPSIR (driving forces-pressure-state-impact-response) framework (summarised in Fig. 9). Interviews were conducted with experts and stakeholders to understand the reactions of authorities and civil society to urban sprawl. The demand for urban land, particularly at the

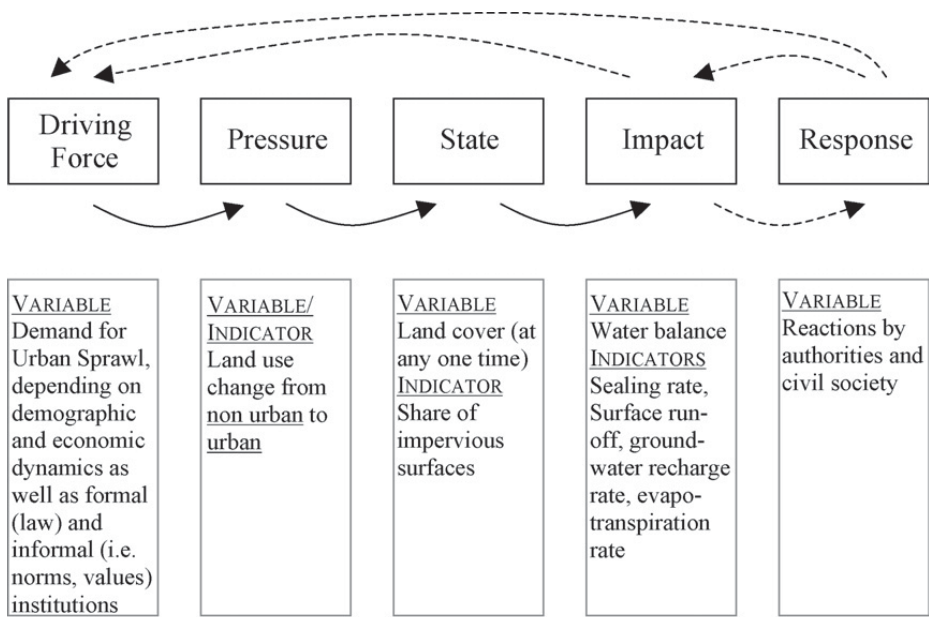


Figure 9. Application of the DPSIR-concept to the issues of urban sprawl and water balance in Leipzig.

fringes of the city, has driven changes in land use and has seen the increase in natural areas of land being covered by impervious surfaces.

The study suggests that although the problem of urban sprawl is generally recognised at all levels of society (including public authorities and suburban advocacy groups), environmental concerns (and the impact on the water balance in particular) are not always perceived to be the most important aspects of urban sprawl.

The response of different sectors of society to urban sprawl appears to depend on a number of factors, including the dynamics of the local population, the influence of organisations concerned about land use change on decision makers and the ability to use events, such as the extreme flooding in Central Europe in 2002, to alert all sectors in society to the issues of changing land use.

Public authorities respond to the impact of urban sprawl on the water balance because:

1.) Public authorities have to manage the consequences of urban sprawl on the water balance, such as dealing with the increased risk of flooding.
2.) The financial implications of urban sprawl for local authorities (e.g. receiving increased revenues from new developments) have a greater impact in the short-term than the accumulated longer-term environmental impact on the water balance.
3.) The desire of local authorities, for whom local taxes are a significant source of revenue, to attract growth to their area can be at odds with the need to protect the environment. Environmental concerns typically focus on other issues, such as the protection of green space.

Federal state authorities in Germany aim to reduce the national rate of land conversion from rural to urban from 105 hectares per day to 30 hectares per day by 2020. The researchers suggest this decision has been taken because of a general concern for the environment, rather than as a result of specific environmental impacts caused by particular problems.

Regional authorities at the sub-national or supra-local level have developed regional plans that include the control of urban sprawl and which consider environmental issues. However, the researchers suggest these plans focus on, for example, the protection of drinking water, rather than preserving the water balance.

Local pressure groups are often more interested in preserving green space or restricting new development in their area because they are more concerned about the value of the land than the environmental impact of urban sprawl. Demands are sometimes made by local groups to off-set the impacts of urban sprawl, for example, building by-pass roads, rather than the halt of urban sprawl itself. Nevertheless, the study suggests that a change of attitudes towards the 'ideal lifestyle' of living in the suburbs could help change urban planning policies. Local pressure groups could play a role in bringing about this shift in the way people view suburban living.

However, national policies are considered to be the most effective means of tackling the driving forces of urban sprawl. At this level, tax disincentives can be set for land use change, although historically, as was the case in East Germany in the 1990s, it was federal government incentives that subsidised development.

The costs of dealing with the potentially greater risk of flooding arising from increased surface run-off can be a large expense on top of development budgets for cities. Although both the amount and type of land, as well as the pattern of land use converted for urban development, influences the water balance, the researchers suggest compact cities are the best choice from an environmental point-of-view, as a greater area of surrounding natural landscape can be retained. This must be considered alongside a general decrease in environmental conditions that has been observed within compactly developed urban areas.

In addition, the researchers suggest that the DPSIR approach can be used as a tool by policymakers to promote efforts to contain urban sprawl by helping different sectors of society understand the feedback between the environmental impacts and the driving forces of urban sprawl.

Sources:

1. Haase, D., Nuissl, H. (2007) Does urban sprawl drive changes in the water balance and policy? The case of Leipzig (Germany) 1870-2003. *Landscape and Urban Planning*. 80:1-13.

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

Further reading:

Scenarios of land use management in the Leipzig-Halle region - an outcome of the EU PLUREL project .

See: http://www.plurel.net/images/D336.pdf
See: http://www.plurel.net/images/D348.pdf

2.2 The impact of urban gardens on the water cycle

Unsealed urban gardens provide patches of natural surfaces that help reduce run-off, reducing the likelihood of urban flooding and replenishing groundwater by allowing rainwater to infiltrate.

Case study 7: Paved gardens in Leeds, UK

One study[1] reveals how individual decisions by home owners to pave over garden surfaces contributed significantly to the long-term build-up of the total area of impervious surfaces in a suburb of Leeds, UK, increasing the incidence of flooding.

Homes in this area are typically semi-detached, with large gardens and space between the homes for driveways. Part of the area was flooded in 2004 after a particularly heavy rainstorm that lasted for three hours. Although various sources of the floodwaters were identified, including flow of water overland, the main reason appears to have been that the stormwater drains were overwhelmed by water flowing down the highway.

Water collected in three locations in the area flooded nearby properties and it is suggested that this was caused by water flowing off paved driveways onto the road (see Fig. 10). One of the flooded areas appears to have been especially affected by dropped kerbs (where pavements are lowered to allow vehicle access), which permitted excess water to back up from the overwhelmed gutters onto the properties.

In 2007, parts of Leeds were flooded again and the study area was once more one of the most seriously affected areas.

The study found that:

1. In 2004, 44.3% (0.52 km^2) of the study area was paved over, up by 12.6% from 1971 when 31.7% (0.37 km^2) of the study area was covered with impervious surfaces.
2. Between 1971 and 2004, the paved areas in gardens increased by 138%, which contributed to 75% of the total increase in paved areas. Buildings (including schools), car parks and roads accounted for the other 25% increase in impervious cover.
3. 90% of houses had paved front gardens in 2004, up from 71% of houses in 1971. Most of the increase was for driveways. Front gardens were defined in this study as spaces to the side of the houses and driveways, irrespective of whether they were at the front, back or side of the house
4. In 1971, driveways were typically the width of a motor car; in 2004, driveways occupied a larger area of the garden, often extending to the boundary of the property replacing the grass or flowerbeds that were more commonly found in 1971.
5. Average run-off increased by 12% in the study area, caused by the increase in impervious surfaces. Peak run-off could see a significantly higher increase, although this was not quantified in the study.

Figure 10. A paved driveway in the study area of Leeds: run-off is likely to drain to the street.

The main reason for this increase in paved gardens has been caused by the householders' desire for larger driveways. Explanations for the growing trend of covering over gardens in the UK include: the higher ownership of cars, problems with on-street parking, inadequate public transport and a move towards low-

maintenance gardens.

This increase in impervious cover has taken place gradually, with the impact accumulating over time. For local authorities, the consequences of dealing with greater risks of flooding include costly upgrades of the drainage system.

At the time the study was published in 2008, a Leeds City Council representative said:

> *"the outcome of this research project supports our opinion of the negative impact that hard paving in residential areas has on drainage. It is recognised nationally that the hard paving of areas – including people's gardens – is a contributory factor in flooding. As a result, the Government has announced that permitted development rights which allow households to pave over their gardens without planning permission will only be applicable if porous materials such as permeable paving or gravel are used….As part of the council's core strategy, we are also looking into including policy which will mean that only porous materials are used in any large scale hard standings such as car parks and event spaces to improve future drainage".*[2]

1. 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.

2. Nawaz, R. (2011). Personal correspondence.

2.3 Soil absorption of stormwater

One consequence of increasing impervious cover in urban areas is that conventional urban stormwater systems with underground piping can be overwhelmed when run-off exceeds the capacity of the system. In these cases, flash flooding can occur.

A shift towards managing stormwater in a manner more aligned with natural processes is proving to be an effective way of reducing the impacts of built urban structures, such as residential developments. Allowing stormwater to infiltrate open ground can effectively reduce the volume of surface run-off, reduce peak streamflows and improve the quality of stormwater entering water bodies. Pollutants, especially hydrocarbons from transport, collect on impervious road and pavement surfaces and are washed off by surface run-off. Soil filters out pollutants in surface water as it percolates downwards, reducing the contaminant load entering streams, rivers and wastewater treatment plants. Surface run-off is better controlled by soils with high infiltration capabilities: development on less permeable soils is therefore preferable.

Case study 8: Drainage systems in The Woodlands, USA

Two related studies have looked at the impact of an ecological engineering approach to handling stormwater in a suburban development near Houston, USA.

The first study[1] compared the impact on downstream floods of two drainage systems found in the development: the use of open grassy swales (open ditches) to collect and detain water in a similar way to natural infiltration of rainwater, and the more conventional approach of channelling stormwater via kerb and gutter, drop inlet and underground pipes to holding areas or stream outlets. The second study[2] examined the impact of different types of planning designs and different soil types on streamflow (watershed runoff).

Both studies focused on The Woodlands development, which is in an area with an average annual rainfall of 840mm and is susceptible to flooding from heavy storms and hurricanes. Started in the 1970s in a pine forest, the development concept was one of the first to be based on the ecological design principles of Ian McHarg. McHarg recommended that development density and land use should be determined by the hydrological properties, or permeability, of the underlying soil. In effect, commercial development and homes should be built on soils with low infiltration capacities (e.g. clay-type

soils), leaving more permeable or sandy soils open, to allow the natural infiltration of rainwater. This is in contrast with the way many developments are planned, as it is easier (and less costly) to lay foundations in sandy soils compared with clay soils.

The Woodlands has been developed in stages. The early development (1975-1976) closely followed McHarg's principles with grassy swales found in areas with soils of high permeability (see Fig. 11). However, there was opposition to the rustic appearance of the swales by some residents, and in later stages of the development, particularly after 1997, soil permeability was not a major consideration in planning. Instead there was a switch to kerbs, gutters and stormwater piping in subdivisions in the area, although major roads still retained the swales (see Fig. 11).

The first study found that, compared with pre-development conditions, the volume of run-off at the watershed level increased by 26% in the area developed with the open swales drainage system. In contrast, run-off increased by 110% in the area developed with conventional piping drainage. Impervious cover was similar in both areas and amounted to 15% of the development area with open drainage and 11% of the development area with conventional drainage. The implication is that the different drainage systems had a significant impact on run-off volumes – open swales allowed a greater volume of water to infiltrate and evaporate before out-flowing to streams.

In addition, streamflows were found to be flashier, or increase quickly after heavy rainfall events, in the conventional drainage area. Streamflows reacted more slowly, similar to natural responses of the original forested area, in the area with grassy swales.

In 1979, and again in 1994, an extreme storm event (greater than one likely to occur once in a hundred years) struck. Whilst areas in nearby Houston were flooded, The Woodlands was not. Another severe storm occurred in 2000, after conventional drainage had been introduced. This time, areas of newer development were flooded, but the original development area was not. Hurricane Ike hit the area in 2008: again, the older parts of The Woodlands with the grass swales were not flooded, but the newer sections of the development were. It is suggested that the open drainage system played a major role in mitigating the impact of the storms and preventing flooding.

A lake in the original Woodlands development area and a reservoir constructed in the later development area were built as flood control devices to detain water run-off. The study found that although the grassy swales were capable of mitigating floods alone, the swales combined with the detention lake in that area was a more effective solution. In the newer development containing conventional stormwater drains, despite the reservoir, the area was still flooded by Hurricane Ike. It appears that the effect of the retention dam was unable to compensate for the traditional stormwater drainage system in extreme rainfall events.

In the second study[2], the impact on watershed streamflow was modelled for various development designs, based on the local soil properties, land use, streamflow data and weather conditions. Five scenarios, representing different development densities and different soil types, were modelled to investigate the impact of extreme storm events on watershed streamflow and flooding: a baseline representing the original forest; two low-density developments – one on sandy-type soil and one on clay-type soil; and two clustered high-density (compact) developments – one on clay-type soil and one on sandy-type soil.

(a) (b)

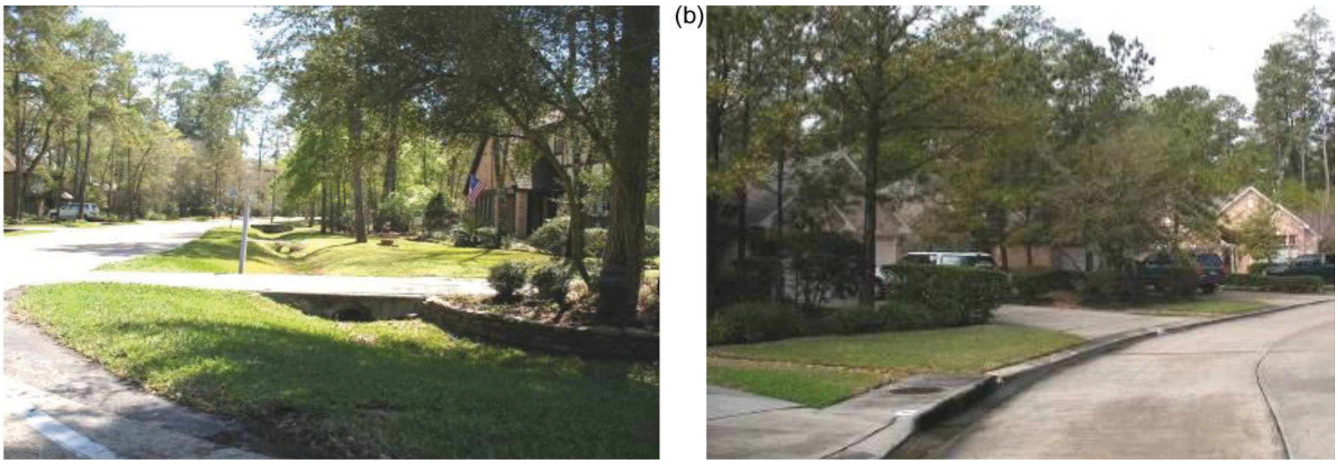


Figure 11. Different drainage systems in The Woodlands. (a) Open surface drainage system in the first two villages. (b) Conventional underground drainage system in later villages.

The results suggest that the best design scenario to reduce stormwater run-off is high density (compact) development on clay soils, and the worst is low-density development on sandy soils. High density development typically concentrates impervious cover and leaves a greater area of uncovered land around clusters of development. Low density development typically creates a greater total area of impervious cover.

In particular, the study found that with small rainfall events, the density of development had more influence on long-term run-off than the underlying soil type:

- compared with the original forest conditions, average watershed run-off from both high-density development scenarios was 40-50% greater, whereas low-density development was 90-100% greater.
- in terms of soil types, low-density development on sandy soils increased annual watershed run-off by 8% compared with low-density development on clay soils. Low-density sandy soil development increased watershed run-off by 34%, compared with high-density sandy soil development.

In contrast, for extreme storm events, the location of developments in relation to soil permeability is more important than the density of development. Flooding is less likely where developments occur on clay soils which preserve the openness of permeable sandy soils and more likely where low-density development takes place on sandy soils.

In addition, the two low-density development scenarios almost doubled sediment loading across the watershed compared with pre-development forest conditions, whilst aquifer recharge was almost halved.

Development of The Woodlands has deviated from the original ideals of building on soil with low permeability and retaining soils of high infiltration capabilities as open space. This includes putting open swales in places based on water circulation patterns, soil type and natural drainage systems. Nonetheless, the researchers conclude that The Woodlands remains a good example of suburban development incorporating eco-friendly design[3].

It is easier to incorporate eco-friendly stormwater management systems in new developments. However, conventional drainage systems can still be replaced with open drainage systems in dense cities when re-development occurs. This has happened, for example in Portland and Baltimore in the US[4]. The United States Environmental Protection Agency (EPA)[5] advocates open drainage (called bioswales or bioretention) techniques as part of Low-Impact Development to manage stormwater. The aim is to manage and treat stormwater run-off onsite rather than piping run-off away to be dealt with off-site.

Onsite stormwater management strategies have been incorporated into Daybreak, a large-scale, ongoing community development in Utah, USA.[4,6,7] Stormwater management systems in the first phase of development (4,127 acres) includes a lake, canal, wetlands, and roadside bioswales. The current manmade lake and the surrounding wetlands promote species diversity with nearly 2.5 times the national average for comparable wetland bird populations.

When completed, the design benefits are planned to include:

- Total retention of all stormwater that falls on the area, including storms of once-in-a-hundred-year intensities, with no connection to the municipal stormwater systems.
- Estimated savings for the development of $30 million in fees associated with the impacts of stormwater and savings of $40 million associated with stormwater infrastructure.

In addition to Daybreak, in 2011 the Landscape Architecture Foundation (LAF) featured another large-scale master-planned community - High Desert (New Mexico, USA) - whose design also placed emphasis on stormwater management and water conservation. Descriptions of the design benefits of High Desert can be found at LAF's Landscape Performance Series website[8].

Sources:

1. Yang, B., Li, M-H. (2010) Ecological engineering in a new town development: Drainage design in The Woodlands, Texas. *Ecological Engineering*. 36: 1639-1650.

2. Yang, B., Li, M-H.(2011) Assessing planning approaches by watershed streamflow modeling: Case study of The Woodlands; Texas. *Landscape and Urban Planning* 99: 9–22.

3. Yang, B., Li, M.-H., Huang, C.S. (submitted). McHarg's ecological planning in The Woodlands: What works and what does not. *Journal of the American Planning Association*.

4. Yang, B. (2011). Personal correspondence.

5. See: http://buildgreen.ufl.edu/Fact_sheet_Bioswales_Vegetated_Swales.pdf

6. Ulam, A. (2010). A New Day? Landscape Architecture Magazine, 100, 98-109.

7. See: http://www.lafoundation.org/research/landscape-performance-series/case-studies/case-study/360/

8. See: http://www.lafoundation.org/research/landscape-performance-series/case-studies/case-study/403/

2.4 Impacts of climate change

A further challenge for urban planners is to account for the potential impacts of climate change on city water systems. Planning for future urban development must take into account uncertainties over the relative impacts of climate change and urban expansion (or contraction in some cases). Climate change is expected to exacerbate water flow problems in urban areas owing to potentially higher temperatures and increased or decreased rainfall.

The greater proportion of impervious surfaces in built-up areas can increase urban temperatures compared with surrounding rural areas. This in turn can influence local microclimates and regional climates if the city is big enough.

Recently, Miao *et al*. (2009)[1] investigated the impacts of urban processes and urbanisation on a localised, summer, heavy rainfall in Beijing using finescale simulations with the Weather Research and Forecasting Model. The results confirm that urban surfaces tend to cause rainfall to be more locally concentrated and that the city plays an important role in determining storm movement and the amount of rainfall.

Although higher urban temperatures should increase the rate of evapotranspiration of water (and therefore counter, to some extent, higher temperatures with a cooling effect), increased surface run-off from impervious surfaces removes rainwater quickly and there is less open ground to soak up water, resulting in less water available for evapotranspiration and cooling.

Both the impact of urbanisation (through an increase in impervious cover) and climate change (through higher temperatures and precipitation rates) are expected to affect future watershed run-off and streamflow.

With an increasing global population, urban areas will expand. How existing city spaces and new developments will cope with the impacts of urbanisation and climate change on the water cycle partly depends on designing and implementing suitable strategies that are able to reduce the harmful impacts of altered water flows, whilst restoring a more natural water balance where possible.

Source:

1. Shiguang, M., Fei, C., Qingchun, L., and Shuiyong, F. (2011) Impacts of Urban Processes and Urbanization on Summer Precipitation: A Case Study of Heavy Rainfall in Beijing on 1 Aug 2006. *Journal of Applied Meteorology and Climatology*. 50: 806-825.

Case study 9: Climate impacts in Brussels, Belgium

Hamdi *et al* (2010) examined the impact of both urbanisation and future climate change on the surface run-off of the Brussels Capital Region (BCR) in central Belgium. In common with many European cities, Brussels has expanded rapidly over the last 150 years, although green space still accounts for 53% of the total area. The study modelled water and energy balances in the BCR based on changes in the area covered with impervious surfaces from 1950 to 2006 and estimated changes in precipitation and temperature under future climate change scenarios. To evaluate the combined impact of climate change and urbanisation, future urbanisation was represented by an increase of 10% or 20% in impervious cover.

1. Effect of historical urbanisation

It was found that there has been a rapid expansion of the urban area: impervious cover increased from 26% of the total area in 1955 to 47% of the total area in 2006.

Previously, the researchers had found that between 1960 and 1999, the increase in impervious surface area has contributed to 45% of the rate of increase in warming observed in the BCR from the urban heat island effect rather than any changes in climate at the local/regional scale.

In addition:

- For every 10% increase in impervious surface area, annual accumulated run-off was estimated to increase by 40%, high streamflow increased by 32% and the flood frequency increased by 2.25 flood events.

- Once impervious cover exceeded 35% of BCR, surface run-off increased the most during the summer months, by 40% for each 10% increase in imperviousness (higher summer rainfall makes flooding in the BCR more likely during the summer).

2. Assessing the relative impacts of climate change and urbanisation.

The study suggests that:

- either increased temperatures or higher temperatures and increased precipitation caused by climate change would affect low streamflow more than an increase in impervious cover.
- However, for high rainfall events the impact of increased impervious cover on summer flooding is four times greater than the influence of higher rainfall projected under climate change scenarios.
- Changes in rainfall under climate change have a greater impact on high flow rates, annual surface run-off rates and seasonal run-off rates than temperature changes under climate change.
- Under warmer climate change projections, evaporation should increase. However, the study found that if urban expansion caused imperviousness to increase by 10% in the BCR, increased surface runoff caused evaporation rates to fall.
- Both an increase in impervious cover (of 20%) and higher rainfall under climate change exacerbate the increases of high streamflow levels.

Despite uncertainties associated with modelling climate change, the researchers suggest understanding the different effects of increased impervious cover and climate change on surface run-off can help urban planners design suitable policies in response to the challenges of greater sealing of urban surfaces and climate change impacts.

Source:

1. Hamdi, R., Termonia, P. and Baguis, P. (2010) Effects of urbanization and climate change on surface runoff of the Brussels Capital Region: a case study using an urban soil–vegetation–atmosphere-transfer model. *International Journal of Climatology*. 31: 1959-1974

2.5 Reducing the impact of impervious cover

A number of different methods have been developed to mitigate the impact of impervious cover.

Case study 10: Canadian Water Network

As part of an initiative to promote successful, innovative approaches to stormwater management, the Canadian Water Network[1] held a series of conferences in 2007 and 2008 with developers to highlight which methods work well under different local, environmental and climatic conditions.

A special issue of the Water Quality Research Journal of Canada[2,3] contained many of the studies presented at these conferences.

Based on the concept of preventing as much rainfall as possible from entering conventional stormwater pipe drainage systems, newer approaches to the management of stormwater seek to intercept, enable infiltration, detention and evaporation of as much of the rainfall as possible onsite in order to maintain the local water balance, prevent flooding, and reduce the pollution of receiving waters.

These innovative approaches have the additional benefit of reducing the amount of pollution from urban areas flowing into local streams.

The shift to innovative stormwater management is designed to operate at three scales: individual property, neighbourhood and watershed scales.

At the property level, suburban developments are common in cities around the developed world. Many houses are built with garages and paved driveways, significantly increasing the area of impervious surfaces. The run-off from these covered areas has traditionally been channelled into stormwater systems with pipes carrying the rainwater into holding areas, wastewater treatment plants or streams. In addition to even greater urban development demanded by growing urban populations, climate change is expected to increase extreme weather events, exacerbating the impact of impervious surfaces on city water systems.

The following table (Table 2) compares innovative approaches highlighted in the conferences with traditional approaches to

Traditional Approach	Innovative Approach
1. Roof runoff is directly conveyed to storm sewers	1. Install green roofs that detain rainfall, allow some evapotranspiration, and reduce and delay storm runoff
2. Collect roof rainwater and discharge it into storm sewers	2. Connect roofwater downspouts to rainbarrels or a storage tank and use the water for indoor or outdoor uses
3. Pave driveways and walkways	3. Minimize impervious surfaces, use pervious pavement, and infiltrate runoff in swales
4. Strip topsoil, allow soil compaction during house construction and roll out thin turf layer after construction	4. Prevent soil compaction, or restore soil porosity after construction, and specify at least 30 cm of topsoil before planting lawn
5. Use piped drinking water for watering lawns and gardens	5. Use collected roof water to water lawns and gardens or develop xeriscapes
6. Remove large trees because of risk of house damage during storms	6. Plant and maintain trees on property for stormwater generation reduction and carbon credit

Table 2: Innovative approaches to rainwater management at the property level

rainwater management at the property level. It is suggested that these different approaches, alone or in combination, can manage stormwater at the property level for 75 to 85% of all rainfall events. Extreme storm events, however, will need extra measures at the neighbourhood or watershed level.

Innovative approaches to manage stormwater at the neighbourhood levels are summarised in Table 3. These measures target run-off from streets and parking lots. Traditionally, streets have kerbs, gutters and dropped driveways that channel water as quickly as possible into underground storm sewer pipes. In contrast, innovative approaches collect water in open systems, connected to ponds and wetlands that can hold excessive run-off during heavy storms. An additional benefit is that pollutant loads can be reduced through infiltration before water flows into wastewater treatment plants, streams, rivers or oceans.

Innovative stormwater management at the watershed level is summarised in Table 4.

Sources:

1. See: http://www.cwn-rce.ca/

2. Water Quality Research Journal of Canada. (2009). Vol. 44 (1): 1–110. Innovative Approaches to Stormwater Management in Canada. See: http://www.cawq.ca/cgi-bin/journal/display.cgi?language=english&pk_journal=85

3. Marsalek, J., & Schreier, H., (2009) Innovation in Stormwater Management in Canada: The Way Forward. *Water Quality Research Journal of Canada*. 44 (1): v-x. http://www.cawq.ca/journal/temp/article/407.pdf

Traditional Approach	Innovative Approach
1. Pave all roads and sidewalks and direct runoff into storm sewers using a curb and gutter system	1. Minimize the width (area) of roads, remove all curbs and gutters and direct runoff into road-side infiltration swales, use pervious pavement (as much as possible)
2. Build a network of storm sewers and direct stormwater runoff into local streams	2. Build stormwater detention ponds and wetlands for large storms to detain runoff and reduce pollutant and sediment loads that enter streams
3. Build parking lots that are impervious and direct the runoff into storm sewers	3. Build parking lots with pervious pavement materials or direct runoff away from storm sewers into detention systems, swales and constructed wetlands
4. Allow contaminants to accumulate on street surface and be washed off by runoff into stormwater conveyance systems	4. Apply source controls by minimizing the use of polluting chemicals, and practicing street sweeping, contaminant retention, and rehabilitation of contaminated areas.

Table 3: Innovative approaches to rainwater management at the neighbourhood level

Traditional Approach	Innovative Approach
1. Stormwater is conveyed through pipes, passes through riparian buffer zones and is released into local streams	1. Create wide riparian buffer zones and create constructed wetlands within these zones to store excess stormwater, retain sediments and pollutants, and filter the water. Minimize or eliminate all stormwater outfalls discharging directly into streams
2. Channelizing urban streams and rivers to increase flow capacity, minimize bank erosion and speed up drainage	2. Maintaining natural river channels to allow lateral flow and storage of stormwater within the riparian zone
3. Floodplain is designated and flood management (protective) structures are built	3. Designate areas within the floodplain and the riparian buffer zone to serve for temporal storage of stormwater during flood events
4. All stormwater systems are connected and their outlets become point sources of pollution discharged into local streams	4. Avoid cumulative effects that increase flow and pollution loads by directing all stormwater drainage to pass through infiltration and detention systems

Table 4: Innovative approaches to rainwater management at the watershed level

2.6 Green roofs

Green roofs are one mitigation method that is popular in parts of Europe, which can reduce run-off from building roofs, moderate urban and building temperatures, reduce pollution loads in run-off from rooftop surfaces, increase the area available for biodiversity and provide a pleasing appearance in an urban setting.

Case study 11: LIFE projects GreenClimeAdapt, Sweden and GRACC, UK

LIFE has been used to further EU knowledge about countering negative impacts from soil sealing. LIFE's work in this field dates back to 1998 when the Programme was involved with establishing 15 different types of green roof tests on a 9500m2 project at Sweden's Augustenborgs Botanical Roof Garden in Malmö. Notable results from water flow studies on lightweight sedum moss roofs found that annual outflows can be reduced by up to 64% through evapotranspiration. Such findings indicate green roofs' potential for reducing flood risks from stormwater peaks.

Further studies revealed that neither the slope nor the length of a 30mm thick sedum moss roof seemed to greatly influence the distribution of water run-off. Introducing drainage layers below the soil tended to increase run-off rates of roof water, and this suggested that the most important factor influencing run-off was the vertical percolation process through the roof's vegetation and the soil.

Ongoing work by Malmö municipality's GreenClimeAdapt[1] LIFE project continues to learn from these outcomes. Covering 45 industrial hectares, the project is testing 600m^2 of alternative green roofing as well as new natural storm water management systems that expect to retain 90% of rainfall over a ten year period, and so radically reduce flood risks. Innovative 'green facades' containing climbing plants are also being trialled by the LIFE project. Two facades were planted in autumn 2010 on the south, west and east sides of an office building and a cold store. Each facade is being closely monitored to investigate their ability to decrease the buildings' energy demands by providing natural shading and insulation functions.

In addition to co-financing the planting of green coverage on urban roofs and facades, other LIFE projects have been promoting the concepts and improving the delivery of green roofing approaches. In the UK for example, LIFE's GRACC project (Green Roofs Against Climate Change)[2] has developed

a new 'GRO Code of good practice for green roofing'[3]. This set of national guidelines is available in an interactive web form and highlights best green roofing practices such as design, construction practice, biodiversity and planting, as well as maintenance.

Jeff Sorrel from the GRACC project explains, "Our new code contains a large amount of useful material including recommendations for the percentage of roof space that should be ideally covered with green cover. In the UK this figure is 80% and the code also sets a standard for green roofs to be around 80mm thick. This is considered necessary to provide a critical mass of substrate to sustain plant cover and biodiversity in our UK climate."

The new code now provides Britain's construction industry with a baseline from which to build on that Mr Sorrel sees as "Important because it represents a common benchmark across the country which will help people understand the longer-term impacts from green roofing".

Construction companies have welcomed GRACC's work and the UK's National Federation of Roofing Contractors note that the GRO code of best practices is the most downloaded document on their website. Green roof trends in the UK are thus on the up and this green growth sector is being further encouraged by GRACC through its co-sponsorship of a green roof award scheme. All entries to the scheme need to comply with GRO Code guidelines and the number of candidates is increasing by around 50% each year. Last year's winner featured 1600m^2 of low impact green roof at a high value heritage site.

Sources:

1. See: http://www.ivl.se/english/startpage/projects/assignments/assignments/greenclimeadapt.5.7df4c4e812d2da6a416800074232.html

2. See http://www.thegreenroofcentre.co.uk/green_roof_code

3. See http://www.nfrc.co.uk/upload/GRO%20CODE%202011.pdf

Case study 12: Rainwater harvesting in Sant Cugat del Vallès, Spain

Urban development is increasing the demand for water in many cities across the world. In Europe, water security is particularly problematic in areas with low rainfall, such as in Southern Europe. Instead of viewing rainwater as a risk to be managed, one study[1] has demonstrated that rainwater harvested in rooftop tanks can be used to reduce overall consumption of drinking water (i.e. water that is of good enough quality for drinking).

A number of municipalities in Catalonia, Spain have introduced water saving regulations to encourage the use of local sources of rainwater, greywater (domestic wastewater suitable for recycling) and groundwater. In 2002, Sant Cugat del Vallès was the first municipality in the Metropolitan Area of Barcelona (MAB) to introduce a building code that required rainwater harvesting systems to be installed in buildings which had more than 300m^2 of garden. This generally applies to multi-family buildings with communal gardens. By 2010, over 40 municipalities in the MAB had introduced similar regulations. Partial subsidies are also available for single family households to install rainwater harvesting systems.

In common with other metropolitan areas in Southern Europe, Sant Cugat del Vallès has grown rapidly, with the associated problems of urban sprawl, including larger, single family households and the high use of water outdoors. Low density areas (mainly single family homes) cover two thirds of the urban area, although two thirds of the population live in high density residential areas and multi-family buildings.

Rooftops represent 13.5% of the low density area and 26.4% of high density residential areas in the municipality, although each type of development has about the same total area of rooftop. Theoretically, collecting rainwater from rooftops could meet about 16% of the total water requirements of Sant Cugat del Vallès.

For single family households, a tank of 22m^3 capacity could meet 61.7% of irrigation requirements and save 42m^3 of drinking water a year.

Rainwater can also be used for toilet flushing and in single family households a tank of 11m^3 would meet 97.9% of the water demand for flushing toilets, saving 28.4m^3 of water a year.

In addition to irrigating gardens and flushing toilets, collected rainwater can be used for laundry washing because dissolved minerals are present only in low levels in rainwater.

In a single family household, a small 13m^3 tank could provide enough water to meet 80% of the demand for both toilet flushing and laundry functions.

For multi-family buildings, 94% of the water used to irrigate gardens could be met by a tank of $45m^3$ capacity, providing a saving of $97m^3$ of drinking water. Multi-family buildings only used the rainwater to irrigate gardens, which was the least efficient use of the water with regards to saving drinking water and costs. Rainwater harvesting in multi-family buildings could meet 48% of the demand for flushing toilets and save $220.5m^3$ of water a year using a tank of $26m^3$ capacity.

It was found that rainwater was most efficient in meeting more than one end-use. However, harvested rainwater is rarely used to flush toilets and clean laundry in the metropolitan area of Barcelona despite the benefits.

Benefits of using rainwater harvesting systems depend partly on the willingness of householders to install and use the water in the most efficient manner. In general, the study found that householders considered the environmental benefits of using harvested rainwater to be more important than the financial aspects. However, the long payback period is a major barrier for homeowners to install rainwater harvesting systems.

Once single-family households have decided to invest in rainwater harvesting systems, they become directly aware of the amount of water collected and used and of the local climate conditions. It is suggested that this awareness can be built on, to develop wider water conservation practices.

In contrast, 70% of people in multi-family buildings were not aware of the rainwater harvesting systems in their building. The remoteness of householders to the installation, management and maintenance of the system probably accounts for this lack of ownership.

Developers consider the installation of rainwater harvesting systems as an additional cost. However, householders' positive perception of rainwater collection and use could be used as a marketing strategy, to encourage greater voluntary installation of the systems.

It is suggested that widespread information campaigns, involving all stakeholders, could increase the use of rainwater harvesting systems, especially for multi-family dwellings.

Source:

1. Domènech, L., Saurí, D. (2011) A comparative appraisal of the use of rainwater harvesting in single and multifamily buildings of the Metropolitan Area of Barcelona (Spain): social experience, drinking water savings and economic costs. *Journal of Cleaner Production*. 19(6-7): 598-608.

Hydrological research gaps identified by researchers of the case studies:

- How much soil sealing can be applied on a watershed, and which spatial patterns can be allowed? At which threshold does the practice start to become unsustainable? This knowledge would help policymakers develop what many may call 'resilience'[1].
- The impact of different forms of semi-sealing on hydrological functioning, such as groundwater recharge, evapotranspiration, surface-run-off and interflow[2] needs to be tested.
- The urban water balance needs to be further analysed to uncover where most uncertainties lie in terms of function, data and knowledge gaps [2].
- There needs to be better links between urban hydrological (water balance) and flood risk research and research into urban droughts and their relation to surface sealing[2].
- The impacts of soil sealing on peak flows (highest stream flow after a precipitation event) need greater consideration[3].
- There need to be better links between engineers and atmospheric scientists seeking to quantify both the role and magnitude of urban evaporation. For example, urban hydrology models - used at the house and street scale do not account for the microclimate and energy use impacts of the city[4].

Sources:

1. Li, M-H. (2011) Personal correspondence.
2. Haase, D. (2011) Personal correspondence.
3. Nawaz, R. (2011) Personal correspondence.
4. Hamdi, R. (2011) Personal correspondence.

Part 3: soil sealing and the urban heat island effect

3.0 Introduction

Manmade landscapes in large towns and cities can affect the local microclimate. Buildings, roads, car parks and pedestrian walkways all absorb heat and increase surface and ambient air temperatures, and heat emitted from the use of energy in cities also contributes to higher temperatures. This can cause urban areas to be considerably warmer than the surrounding rural areas - a well-documented phenomenon known as the 'urban heat island effect'. The heat island effect varies and depends on a number of factors, including: the size and location of the city; the configuration of buildings, paved areas and vegetation cover; and the number of people living and working in the city.

3.1 Land use and surface temperatures

Rapid urbanisation in many parts of the world has caused a change in the use of land and surfaces covering the land (land-use/cover change (LUCC)). Changing land cover affects surface temperatures by changing moisture and optical properties of the land and is particularly pronounced when natural landscapes are covered with impermeable surfaces.

Developing countries with high economic growth in particular have experienced an accelerated pace of urban development. This trend has been evident in China, where LUCC has had a range of environmental impacts, including the urban heat island effect.

Case study 13: Land surface temperatures in Kunming, China

Land surface temperatures (a common measure of the urban heat island (UHI) effect, typically measured from satellites) that have changed in response to land use change have been investigated in Kunming city, in south-west China. Kunming has seen extensive changes in land use caused by rapid economic growth and urbanisation. The urban area grew by almost 40% from 184.4 km^2 in 1992 to 257.8 km^2 in 2005; the climate is subtropical highland with warm, wet summers and cold, dry winters.

This study[1] compared the estimated land surface temperatures (LST) in Kunming in 1992 and 2006 in relation to land use changes.

It was found that (see Fig. 12):

- For forest land converted into built up land, the LST increased by about 3.4 kelvin (K)
- For agricultural land converted into built-up land, the LST increased by about 1.9 K
- For barren land converted into built-up land, the LST increased by around 1.7 K
- For agricultural land converted to forests, the LST decreased by about 3.1 K
- For forest land converted into agricultural land, the LST increased by about 1.5 K

LUCC has had a widespread impact on the thermal environment in Kunming City: green space was lost between 1992 and 2006 at the same time that urban areas expanded. No major changes were found in the pattern of water areas during this time. (See Fig. 12).

In particular, changes in LST revealed the growth in urban sprawl on the edges of the city that occurred between 1992 and 2006. Vegetated areas were converted into built-up or barren land, although on the eastern side of the city, some non-vegetated areas were converted into vegetated areas. The transition from vegetated areas to barren and built-up land has changed the surface energy balance and modified

thermal properties of the land surface in these areas, producing a warmer environment.

These changes can be seen in figure 12(b) where the increased LST is evident around the urban core, whilst decreased LST can be seen in eastern Kunming.

Overall, there are more areas of higher LST in 2006, compared with 1992, and this is related to the LUCC (mainly vegetated areas converted into built areas or barren land). However, there are some localised cooler spots as a result of green policies recently implemented in the city. These policies have included efforts to increase the area of green strips along a central canal and planting on barren land in the eastern part of the city, which has created or increased the area of several urban parks. As an example, it was found that temperatures in newly developed green space and corridors were about 3-4 K lower than in built-up areas.

Source:

1. Zhou, X. and Wang, Y-C. (2011) Dynamics of Land Surface Temperature in Response to Land-Use/Cover Change. *Geographical Research*. 49(1):23-36.

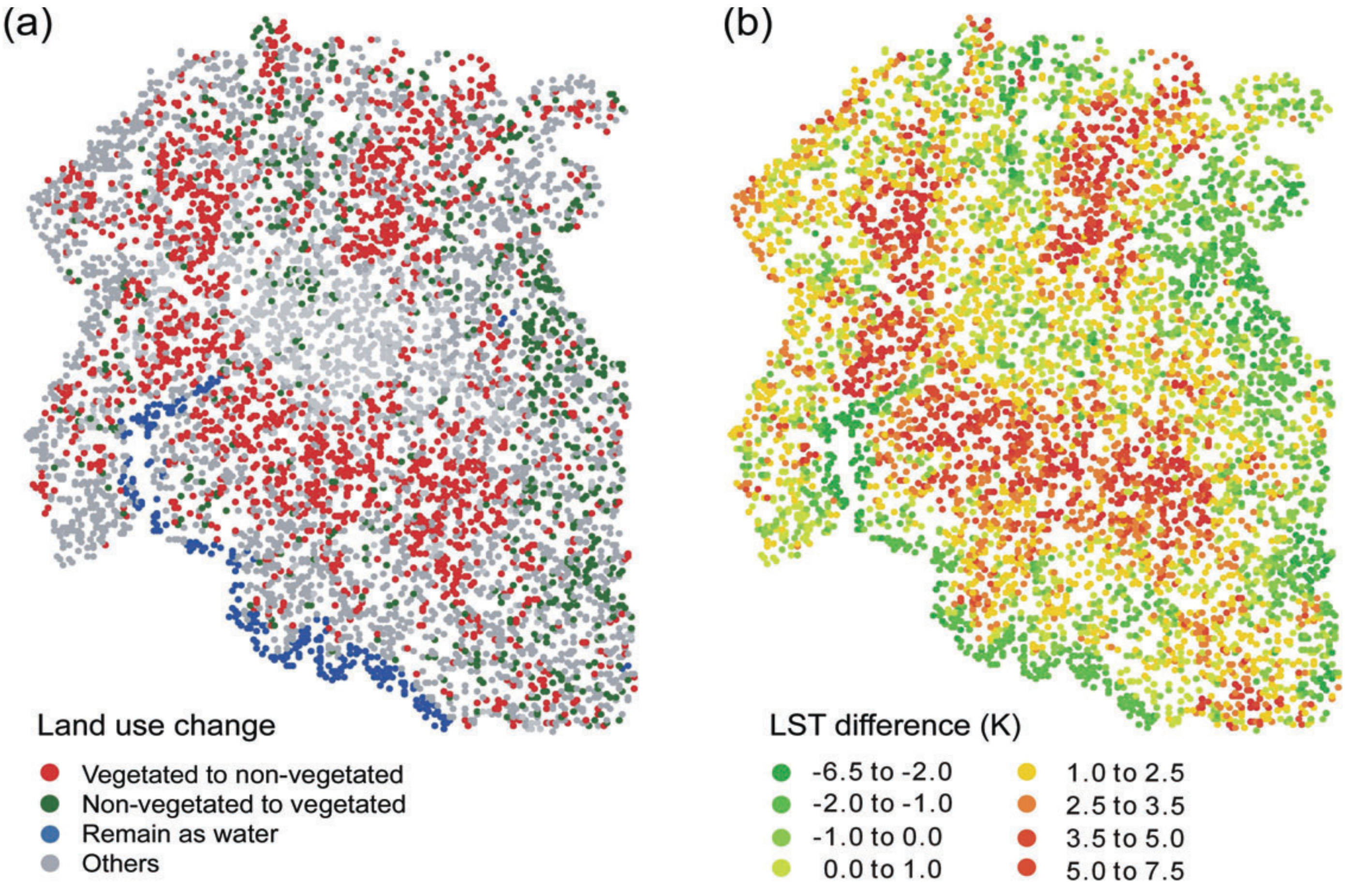


Figure 12. Spatial correspondence in Kunming between (a) changes in land use and (b) differences in land surface temperature (LST) between 1992 and 2006. Each dot represents one of the 5929 sampled points.

3.2 Urban planning impacts on local climate and temperatures

Urban planning directly affects the amount of different land covers and the pattern of urban infrastructure. The change in surface characteristics created by urbanisation influences the atmospheric properties of a region by changing the surface energy balance and causes local differences in climate between rural and urban areas, in addition to variations within urban areas.

Given the global trend towards the expansion of urban areas, and the added impact climate change is expected to have globally and regionally, understanding the influence of urban design on urban climate variations is an essential part of creating sustainable and liveable urban environments.

Case study 14: Urban planning and temperatures in Beijing, China

To understand how planning in urban areas can affect the local climate and the temperature differences across cities, this study has investigated the relationship between planning indicators and urban temperatures measured as daily maximum and minimum surface temperatures and the timing of peak daily temperatures, based on measurements from weather stationsin Beijing, China[1].

Beijing has a humid, continental climate with hot, humid summers and cold, dry winters. As rapid urbanisation over the last few decades has had an impact on the urban thermal environment, part of Beijing's master plan for 2004-2020 includes making the city 'liveable'.

For this study, 11 sample sites, representing a variety of land cover types and urban physical and development patterns in the urban environment were selected throughout central Beijing along the north-south axis to investigate the urban heat island effect.

In particular, the influence of different urban planning indicators, such as total building floor area, building density, building height limit, green cover ratio (ratio of total area of all green spaces (measured above the tree canopy to include the role played by tree canopies in lowering surface temperatures and increasing humidity in the urban setting) to area of the land), and factors affecting the minimum distance between buildings on local climate were explored. Climate indicators chosen for this study were: the daily maximum and minimum surface temperatures and the timing of daily peak temperature.

A surface energy balance model was used to simulate the daily maximum and minimum surface temperatures and the time when the peak temperature occurred during the summer season.

The highest surface temperatures (just under 40°C) occurred in the most central area (the Old Town, featuring courtyards surrounded on all four sides by buildings). The next highest surfaces temperatures occurred in the Core area surrounding the Old Town area. The Core area is typified by new high-rise buildings. Unsurprisingly, the lowest surface temperatures were found in parks, emphasising the importance that green spaces play in modifying the UHI effect. The lowest surface temperature in the sites considered in the study was around 22°C.

Together, the green cover ratio and the floor area ratio could explain around 94-99% of the differences in maximum daily temperatures; the green cover ratio and building height could explain 99% of the difference in the daily minimum surface temperatures; and the building floor area ratio, green cover ratio and building density could explain around 99% of the difference in the timing of the occurrence of the daily peak temperature.

These simple relationships between climate indicators and urban planning indicators can help urban planners incorporate climate adaptation measures at the beginning of the planning process in order to minimise the negative impact of development and climate change on urban temperatures in a city.

Source:

1. Zhao, C., Fu, G., Liu, X., Fu, F. (2011). Urban planning indicators, morphology and climate indicators: A case study for a north-south transect of Beijing, China. *Building and Environment.* 46: 1174-1183.

3.3 Heat islands and social inequalities

Increased urban temperatures can cause discomfort to city dwellers. In addition, the urban heat island effect contributes to heat waves, which can kill many vulnerable people, as occurred during the heat wave that hit Europe in the summer of 2003, when about 15,000 people died in France[1].

Although heat waves are generally considered to be natural hazards, the impact on different socioeconomic groups can vary considerably. For example, previous studies have linked deaths related to heat waves in cities with social characteristics, including socioeconomic status, lifestyle and different neighbourhood characteristics.

Source:
1. See: Report on excess mortality in Europe during summer 2003 http://ec.europa.eu/health/ph_projects/2005/action1/docs/action1_2005_a2_15_en.pdf

Case study 15: Temperature hotspots in Gwynns Falls, USA

By examining the urban heat island effect (UHI) in conjunction with LST, (land surface temperature, a common measure of the UHI), urban land-use/land cover and social factors, a study[1] in the Gwynns Falls watershed in Maryland, United States, investigated the pattern of LST and whether the pattern in a neighbourhood was related to social characteristics of that neighbourhood.

The study confirmed that within a city, temperatures can vary widely, causing local 'hotspots' within a heat island. These hotspots are often neighbourhoods that are home to residents with a lower socioeconomic status than those in cooler neighbourhoods.

The study area includes part of Baltimore City and extends into Baltimore County, Maryland, USA and encompasses urban, suburban and rural land landscapes and a wide spectrum of residents characterised by their socioeconomic status. For example, the average household income in the suburban area was about $52,400, twice as much as the average household income in the urban area ($25,200).

The study area was divided into 298 block groups and average LSTs during summer, as an indicator for neighbourhood temperatures, were calculated for each block. The researchers examined LST in relation to land cover and socioeconomic status, which was characterised by economic status, education, ethnicity, age, lifestyle and the incidence of crime (see Fig. 13).

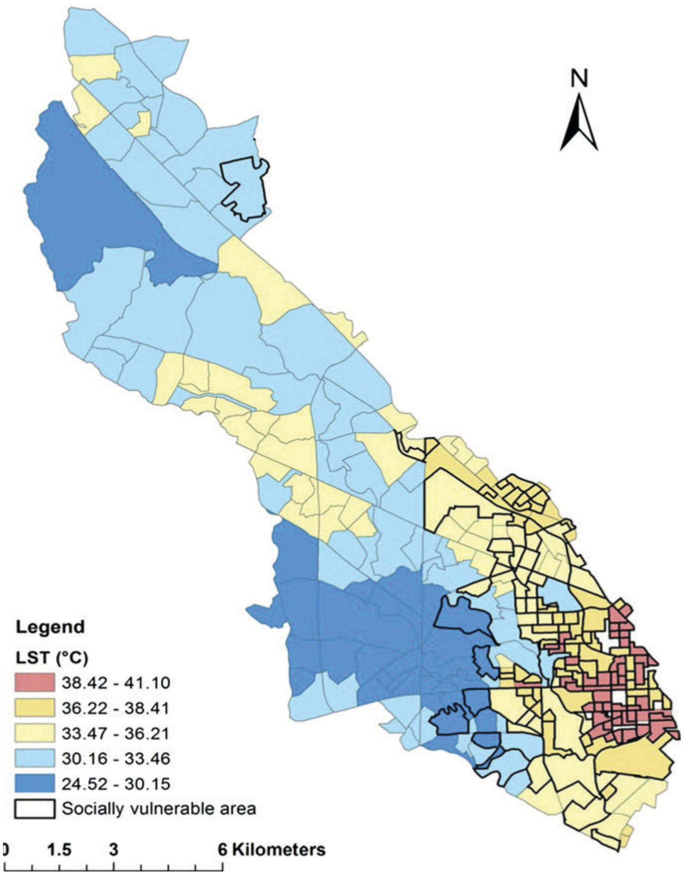


Figure 13. Land surface temperature and socially vulnerable areas, in Gwynn Falls watershed

Within this area, there was a large range between the lowest and highest LST, which varied from 24.52ºC to 41.10ºC. This distribution of heat means that people in different areas of the same region could experience very different comfort levels, with some people feeling no discomfort but others exposed to high temperatures comparable to those of a heat wave. Vegetation cover and impervious surfaces were shown to have a significant impact on the LSTs, with higher temperatures associated with a larger percentage of impervious cover. This implies that fine scale differences in land cover can significantly affect LSTs. In addition, the hottest neighbourhoods were mostly found in the central areas of the city.

In general, the hottest neighbourhoods tended to be where residents were on lower incomes, were less educated, and more likely to be from ethnic minorities, elderly and/or living in poverty. Out of 49 blocks with the highest LST, 46 were in areas of social vulnerability, mostly in the central area. These neighbourhoods may be at increased risk of excessive heat exposure, yet people with a lower socioeconomic status tend to have fewer personal resources to deal with the effects of heat exposure.

For urban managers, this method can be used as a tool to identify those areas where residents are most in need of intervention from excessive heat, helping to prioritise resources. For example, when the LST is combined with selected indicators of vulnerability that are above a certain threshold, blocks can be identified that are hotter than the average LST and have residents below the average of the social indicators. Previous studies suggest these residents are more vulnerable to heat-related mortality and tailored help can be given based on the selected indicators. For example, poorer residents might not be able to afford air conditioning and high crime areas might prevent people opening windows, especially at night. Appropriate strategies, such as providing air conditioned centres, could be designed to help the most vulnerable.

In addition, these maps can be used to prioritise areas that would benefit most from mitigation strategies, such as planting trees to reduce local temperatures, which would in turn reduce the amount of energy needed for air conditioning. There are plans for the tree canopy in Baltimore City to increase by 46.3% by 2030-2036, particularly in locations with extensive, connected areas of impervious cover. By taking into account the relationships discussed in this study, the results could help planners decide the best places to plant the trees for maximum benefit to the most vulnerable citizens without the resources to cope with heat stress.

Source:

1. Huang, G., Zhou, W., Cadenasso, M.L. (2011) Is everyone hot in the city? Spatial pattern of land surface temperatures, land cover and neighborhood socioeconomic characteristics in Baltimore, MD. *Journal of Environmental Management*. 92: 1753-1759.

3.4 Heat island mitigation strategies

Various methods can be used to mitigate the impact of higher urban temperatures. These include 'technical solutions', such as light-coloured roofs, 'green' roofs, and making paved areas of light-coloured materials, as well as more natural solutions, e.g. enlarging the green areas in cities, for example, by planting more trees and growing vegetation up the sides of buildings.

Large areas of open impervious surfaces, such as car parks, create warmer surface temperatures during summer months. Altering the surface of the car parks is one of the options that can be used to mitigate the urban heat island effect.

Case study 16: Grass-covered car parks in Osaka, Japan

This study[1] has measured the decrease in surface temperatures achieved by converting asphalt-covered car parks to grass covered car parks by reducing the amount of heat stored in the impervious asphalt surface. A public car park in Osaka, Japan, where individual parking spaces are rented out and maintained by different private companies, was the focus of this study. Individual parking spaces had different configurations of grass and materials to support the weight of the car. For instance, parking spaces with no grass had supporting materials such as concrete or wood;

other parking spaces had varying amounts of grass arranged in different configurations (e.g. the support for the weight of the cars could be wood or concrete, with grass planted in the gaps. The grass within an individual parking bay could be connected throughout or disconnected). (see Fig. 14). Grass conversions were laid over the existing asphalt cover.

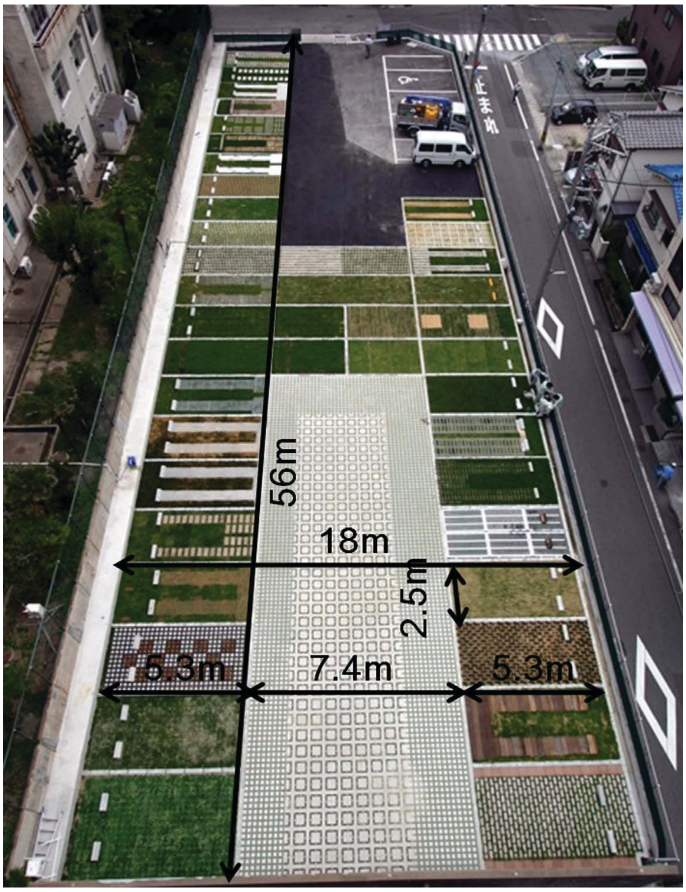


Figure 14. Overall view of the study car park in Osaka.

The changes in surface temperatures on different types of surfaces in each parking space were measured from thermal images taken using an infrared radiation camera. The average surface temperature across the whole of the car park was then calculated from the thermal images. In addition, the radiation transmitted from individual parking spaces and the underground temperatures were measured.

For a summer day with good weather, as the air temperature reached a maximum of just over 32°C at 14:00, the average surface temperature of the asphalt at the same time was nearly 55°C; the average surface temperature of grass was about 40°C; of wood was around 61°C; and of concrete was about 51°C. Wood has a low heat capacity explaining the higher surface temperatures during the day (and lower at night) compared with the other materials. With the exception of the wood surface, the surface temperature of the asphalt was always higher than the other materials, due to the thermal storage of daytime solar radiation of asphalt.

In addition, as the ratio of green surface area increased, the mean surface temperature of the car park was shown to decrease. For example, at midday on a summer day with an average air temperature of around 30°C, the average surface temperature of the car park would be 47.5°C with a 10% grass cover. If the grass cover was 100%, the average surface temperature of the car park would be around 40°C .

Source:

1. Takebayashi, H., Moriyama, M. (2009) Study on the urban heat island mitigation effect achieved by converting to grass-covered parking. *Solar Energy*. 83: 1211-1223.

Case study 17: Photovoltaic cover, Phoenix, USA

In hot, dry climates photovoltaic panels can be used as shade cover over surface pavements, with the additional benefit of providing renewable energy.

In a small-scale experiment in Phoenix, USA, conducted during the summer months, Golden *et al.*[1] investigated the micro-benefits of using photovoltaic cover (canopies) over paved areas as a mitigation strategy for the urban heat island effect in hot, dry regions. The efficiency of photovoltaic panels was compared with a strategy of using tree cover to reduce surface temperatures.

The effectiveness of using tree cover to shade urban pavements and lower temperatures depends on the type of trees, local climate and position of the trees. Trees lower air temperatures through shading and evapotranspiration. When first planted, trees require water to become established: in drought conditions, trees can become stressed, requiring more water. When planted in car parks, trees can be affected by restricted access to water, nutrients and space around the root zone, in addition to the impact of higher root temperatures under asphalt and concrete cover. Trees also take up some of the available parking area because of the need for large area of open ground around the tree trunk base.

The study found that the tree cover reduced the temperature by

Figure 15. Aerial view of the subject research site for PV canopy coverage shows (a) PV modified parking canopies and (b) conventional parking canopies, Phoenix, Arizona.

a maximum of 3.5°C during the day, compared with unshaded areas. At night the ambient air temperature under the trees was about 1°C higher than the ambient air temperatures in the open parking area.

Shading car park surfaces with canopies reduces the solar energy reaching the surface of ground, therefore decreasing surface temperatures. The study found that the unshaded parking area had the highest maximum temperature, whilst the surfaces shaded by either conventional or photovoltaic (PV) canopies had lower, but similar surface temperatures. For example, the difference between the average maximum and the minimum temperatures on the fully exposed pavement was 37°C, whereas the daytime variation for the pavement shaded by either type of canopy was around 10.5°C (see Table 5).

When the mitigation benefits of reducing surface pavement temperatures by the use of tree shade and shade provided by photovoltaic canopies were compared, car park surfaces covered with PV canopies had a 13.2°C reduction in surface temperature compared with exposed surfaces. In comparison, the surface temperature of the paved area under the tree was reduced by 6.2°C compared with the near-by exposed area. Although canopy supports in the ground reduce the total size of the pavement available for parking, the footprint of the supports would not be as large as the dirt wells needed around trees for optimal growth.

However, using PV canopies has additional benefits. As well as lowering ground surface temperatures, PV canopies are also a source of renewable electricity, which can be used to supplement the base load and peak power demands of electricity for local buildings, signs and municipal requirements.

PV cover is most suitable for larger parking areas, such as in schools and commercial areas. In addition, the cooling effects of PV canopies are felt immediately; whilst the benefit from trees is delayed, sometimes for years, until the trees are well established.

In addition to the impact on human comfort caused by high temperatures on unshaded pavements, the large temperature fluctuations create severe expansion and contraction of the pavement material, resulting in a loss of elasticity and resilience. Coupled with degradation of the pavement material under such high temperatures, pavements become hard and brittle. Decisions to use PV canopies should also include the life cycle costs and savings associated with a longer life-time use of pavements shaded from the radiation of the sun.

Source:

1. Golden, J.S., Carlson, J., Kaloush, K.E., Phelan, P. (2007) A comparative study of the thermal and radiative impacts of photovoltaic canopies on pavement surface temperatures. *Solar Energy*. 81: 872-883.

Pavement coverage	Mean maximum temperature	Mean minimum temperature	Mean average temperature
Fully exposed pavement (Ψ_{sky} 0.90)	146.2 °F/63.5 °C	83.3 °F/28.5 °C	110.5 °F/43.6 °C
Under conventional canopy (Ψ_{sky} 0.11)	99.9 °F/37.7 °C	81.1 °F/27.3 °C	90.3 °F/32.4 °C
Under PV modified canopy (Ψ_{sky} 0.11)	98.7 °F/37.0 °C	81.9 °F/27.7 °C	89.7 °F/32.1 °C

Table 5. Mean pavement surface temperatures for various types of coverage

Case study 18: Advanced cooling materials, Greece

One key factor in mitigating the urban heat island effect is to substitute more traditional materials used to construct buildings, roads and pavements with cooler materials. A recent study[1] has reviewed the development of new generation materials and techniques used to mitigate the urban heat island effect.

Cool materials are those that are highly reflective. They have a surface with a high solar reflectance (SR) or ability to reflect the sun's radiation and a high infrared emittance, which is a measure of a surface's ability to release absorbed heat. A surface made of a cool material would have a lower surface temperature in the sun compared with a similar surface with lower solar reflectance and infrared emittance properties.

The solar reflectance index (SRI) incorporates the solar reflectance and the infrared emittance and is another measure of how cool a material is. Compared with hot materials, cool materials have higher SRI values: the cooler the material, the higher the SR values, and the hotter the material the lower the SRI values – very hot materials can have negative values.

Cool materials are available for roofs, roads and pavements.

Commonly used cool materials for roofs come in a range of options. Their thermal properties compared with more conventional materials, are shown in Table 6. For example, surface temperatures of materials with low solar reflectance and high infrared emittance, such as black gravel or asphalt shingle, can climb to 75-80ºC, compared with surface temperatures of about 45ºC for cool materials (e.g. cool white coatings or white membranes).

Cool materials can be used for roads, car parks and pedestrian areas to reduce the impact of hot surfaces during the daytime and the release of heat during the evening.

Compared with traditional pavements, which are typically made with impervious materials, such as asphalt or concrete, cool pavements are made with materials that can lower surface temperatures. This reduces heat released from the pavements, which reduces ambient air temperatures. Cool materials can, for example, have a higher surface reflectance

Material	Solar reflectance	Infrared emittance	Solar reflectance index
Coatings			
White	0.70–0.85	0.80–0.90	84–113
Aluminum	0.20–0.65	0.25–0.65	−25 to 72
Conventional black	0.04–0.05	0.80–0.90	−7 to 0
Cool black	0.20–0.29	0.80–0.90	14–31
Conventional dark colored coatings	0.04–0.20	0.80–0.90	−7 to 19
Cool dark colored coatings	0.25–0.4	0.80–0.90	21–45
Asphalt shingles			
White asphalt shingle	0.20–0.30	0.80–0.90	15–28
Black	0.04	0.80–0.90	−7 to −1
Dark colored conventional asphalt shingles (using a two-layer process)	0.05–0.10	0.80–0.90	−6 to 6
Cool colored asphalt shingles (using a two-layer process)	0.18–0.34	0.80–0.90	11–37
Tiles			
Terracotta ceramic tile	0.25–0.40	0.85–0.90	23–45
White clay tile	0.60–0.75	0.85–0.90	71–93
White concrete tile	0.60–0.75	0.85–0.90	71–93
Grey concrete tile	0.18–0.25	0.85–0.90	14–25
Dark colored concrete tile	0.04–0.40	0.85–0.90	−4 to 45
Cool dark colored concrete tile	0.40–0.60	0.85–0.90	43–72
Membranes			
White membrane	0.65–0.85	0.8–0.90	76–107
Black	0.04–0.05	0.8–0.90	−7 to 0
Metal roof			
Unpainted	0.20–0.60	0.05–0.35	−48 to 53
Painted white	0.60–0.75	0.8–0.90	69–93
Dark conventionally colored	0.05–0.10	0.8–0.90	−6 to 6
Dark cool colored	0.25–0.70	0.8–0.90	21–86
Build up roof			
With asphalt	0.04	0.85–0.90	−4 to −1
With dark gravel	0.08–0.20	0.8–0.90	−2 to 19
With white gravel	0.30–0.50	0.8–0.90	27–58
With white coating	0.75–0.85	0.8–0.90	93–113
Modified bitumen			
With mineral surface capsheet	0.10–0.20	0.85–0.95	4–21
White coating over mineral surface	0.60–0.75	0.85–0.95	71–94

Table 6. Representative values of measured solar reflectance and infrared emittance of commonly used roofing materials

which reduces the heat absorbed by the pavement; or can be made of partially permeable materials, which have a cooling effect when rainfall (that has collected in the semi-permeable material) evaporates.

One issue with light coloured materials with a high solar reflectance used for cool pavements is that they could create glare, for example, when used on roads. Alternative cool materials that are a dark colour can be used instead.

In one experiment by Synnefa *et al*[2], five thin samples of asphalt coloured with special pigments and aggregates were tested for their ability to lower surface temperatures compared with a sample of conventional asphalt.

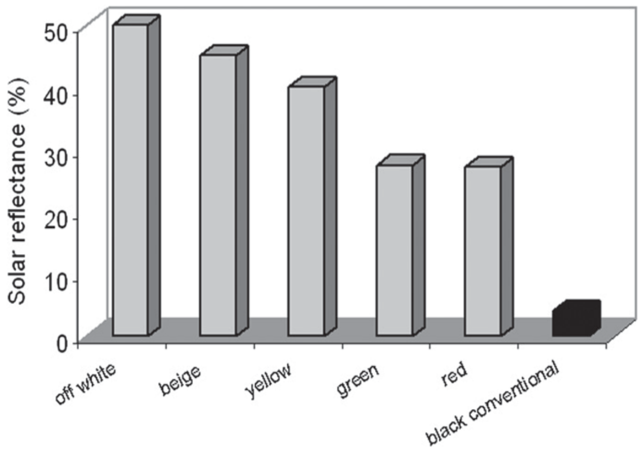


Figure 16: The solar reflectance of the five tested colour thin layer asphalt samples and the conventional black asphalt.

All five materials had a higher solar reflectance and lower surface temperatures than the conventional black asphalt sample. For example, the solar reflectance of the off-white sample was 55% compared with 4% solar reflectance for the black sample.

This difference is due mainly to the high near infrared solar reflectance of the coloured samples. For example, 63% for the off-white sample compared with 4% for the black sample in the near-infrared range.

In addition, reflectance in the visible part of the spectrum was determined by the colour of the sample. For instance, the off-white sample had the highest visible reflectance (45%) compared with the black conventional asphalt sample (3%).

All five coloured samples were found to have lower surface temperatures than the black asphalt sample. The average daytime temperature for the off-white sample was 39°C, compared with an average daytime temperature of 46.7°C for the black sample. The average maximum daytime temperature of the off-white sample was 48°C, compared with an average maximum 60°C for the black sample, meaning that the biggest difference in surface temperature, 12ºC, was found between the off-white asphalt sample and the conventional black asphalt sample. This demonstrates that lower surface temperatures result from surfaces with higher solar reflectance, as less solar radiation is absorbed by the sample.

A modelling analysis of a section of a road in Athens, Greece, suggested that coating the black asphalt on a road with a thin layer of the off-white asphalt could lower average air

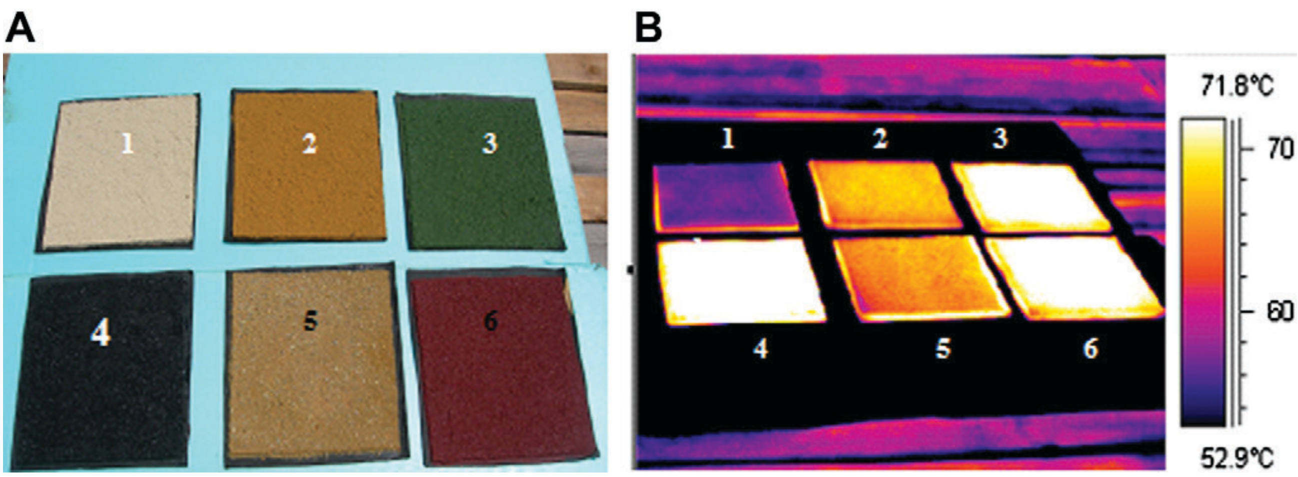


Figure 17. Visible (A) and infrared (B) images of the five colour thin layer asphalt samples and black conventional asphalt sample: 1. off-white, 2. yellow, 3. green, 4. black (conventional) 5.beige, 6. red.

temperatures by 5ºC in summer when wind speeds are low.

Cool materials may reduce urban temperatures when used properly. Urban planners and policymakers should consider this new technology when designing urban projects. However, it is necessary to ensure that the proper standards on the performance of the materials have been evaluated[3].

Temperatures in Athens are increasing: the maximum summer temperatures have shown an upward trend between 1890 and 2007. In addition, the number of days in summer with temperatures above 37°C is increasing and the number of consecutive days with temperatures above 35°C is also rising. The frequency of heat waves is increasing: the intensity of the UHI effect in 2007 was close to 10°C.

The Flisvos project is the design of a coastal park in Athens using green spaces and cool materials to lower ambient temperatures in the summer months. Thermal images taken in 2010 (see Fig. 18 (a.) and (b.)) demonstrate the degree of cooling achieved by the use of cool pavements.

Measurements have been performed before and after construction of the cool pavements, the use of cool materials has reduced the maximum ambient temperature by 1.5ºC. In addition, the surface temperature has been reduced by at least 5ºC (see Fig. 18).

Since the construction of the park, it has been estimated that thermal comfort has improved by 30%-60%.

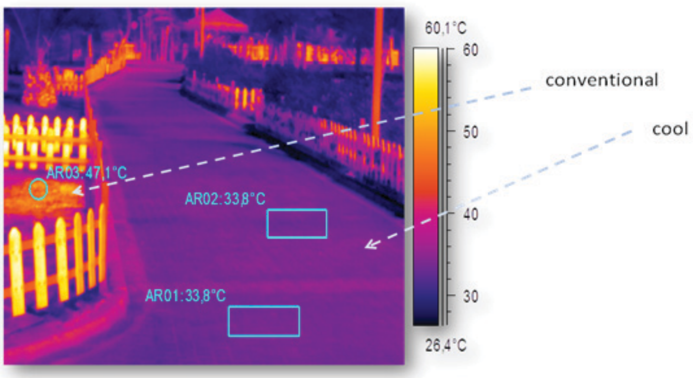
Sources:

1. Santamouris, M., Synnefa, A., Karlessi, T. (2011) Using advanced cool materials in the urban built environment to mitigate heat islands and improve thermal comfort conditions *Solar Energy*. Doi:10.1016/j.solener.2010.12.023.

2. Synnefa, A., Karlessi, T., Gaitani, N. (2011) Experimental testing of cool colored thin layer asphalt and estimation of its potential to improve the urban microclimate. *Building and Environment*. 46: 38-44.

3. Santamouris, M. (2011). Personal correspondence.

A.



B.

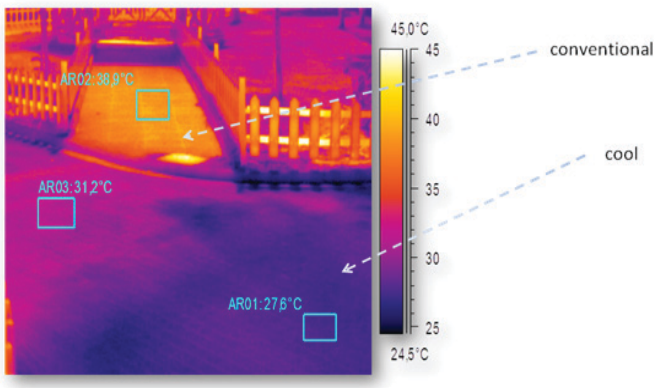


Figure 18. Thermal images demonstrating the cooling effect of using cool paving materials. a.) conventional materials are 47.1ºC. Cooler materials are 33.8ºC. b.) conventional materials are 38.9ºC. Cooler materials are 27.6ºC and 31.2ºC.

Additional sources of information

Burian, S.J., Pomeroy, C.A. (2010). Urban Impacts on the Water Cycle and Potential Green Infrastructure Implications. In: Aitkenhead-Peterson, J. and Volder A. (eds.) Urban Ecosystem Ecology. Agronomy Monograph 55. Madison: American Society of Agronomy, Crop Science Society of America, Soil Science Society of America.

European Commission. Joint Research Centre. Land Management and Natural Hazards Unit. (2011) Soil Themes> Soil Sealing. [Online] Available from: http://eusoils.jrc.ec.europa.eu/library/themes/Sealing/ [Accessed 1 May 2011]

European Commission (2011) The Soil Thematic Strategy [Online] Available from: http://ec.europa.eu/environment/soil/three_en.htm [Accessed 1 May 2011]

European Environmental Agency. (2011). Urban Soil Sealing in Europe [Online]. Available from: http://www.eea.europa.eu/articles/urban-soil-sealing-in-europe [Accessed 1 May 2011]

Heisler, G.M., Brazel, A.J. (2010). The Urban Physical Environment: Temperature and Urban Heat Islands. In: Aitkenhead-Peterson, J. and Volder, A. (eds.) Urban Ecosystem Ecology. Agronomy Monograph 55. Madison: American Society of Agronomy, Crop Science Society of America, Soil Science Society of America.

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

Niemelä, J., Breuste, J. H., Guntenspergen, G. et al. (eds.) (2011) Urban Ecology: Patterns, Processes, and Applications. Oxford: Oxford University Press.

Piorr, A., Ravetz, J., Tosics, I. (eds.) (2011) Peri-urbanisation in Europe: Towards European Policies to Sustain Urban-Rural Futures. Berlin: University of Copenhagen /Academic Books Life Sciences.

Turner, S. (2002) Proceedings of the Technical Workshop on Indicators for Soil Sealing European Environmental Agency. Technical Report No. 80. (2002). [Online]. European Environmental Agency. Available from: http://www.eea.europa.eu/publications/technical_report_2002_80. [Accessed 1 May 2011]

U.K. Parliament. Environment and Energy. (2006). UK Soil Degradation POSTNote 265. [Online] Available from: www.parliament.uk/documents/post/postpn265.pdf [Accessed 1 May 2011]

U.S. Environmental Protection Agency. (2011). Heat Island Effect. [Online]. Available from: http://www.epa.gov/heatisland/ [Accessed 1 August 2011]

U.S. Environmental Protection Agency. (2011). Basic Information. [Online]. Available from: http://www.epa.gov/heatisland/about/index.htm [Accessed 1 August 2011]

U.S. Environmental Protection Agency. (2011).Reducing Urban Heat Islands: Compendium of Strategies Trees and Vegetation. [Online]. Available from: http://www.epa.gov/heatisland/resources/pdf/TreesandVegCompendium.pdf [Accessed 1 August 2011]

U.S. Environmental Protection Agency. (2011). Reducing Urban Heat Islands: Compendium of Strategies Green Roofs. [Online]. Available from: http://www.epa.gov/heatisland/resources/pdf/GreenRoofsCompendium.pdf [Accessed 1 August 2011]

U.S. Environmental Protection Agency. (2011). Reducing Urban Heat Islands: Compendium of Strategies Cool Roofs. [Online]. Available from: http://www.epa.gov/heatisland/resources/pdf/CoolRoofsCompendium.pdf [Accessed 1 August 2011]

U.S. Environmental Protection Agency. (2011). Reducing Urban Heat Islands: Compendium of Strategies Cool Pavements. [Online]. Available from: http://www.epa.gov/heatisland/resources/pdf/CoolPavesCompendium.pdf [Accessed 1 August 2011]

U.S. Environmental Protection Agency. (2011). Reducing Urban Heat Islands: Compendium of Strategies Heat Island Reduction Activities. [Online]. Available from: http://www.epa.gov/heatisland/resources/pdf/ActivitiesCompendium.pdf [Accessed 1 August 2011]

This In-depth Report is published by the European Commission's Directorate-General Environment and edited by the Science Communication Unit, the University of the West of England (UWE), Bristol. Email: sfep.editorial@uwe.ac.uk

All images, figures and tables are copyrighted and reprinted with permission from the following sources::

Front cover: Science Communication Unit, UWE;
Page 2 : Science Communication Unit, UWE;
Page 5: Figure 1. Sutton, P.C., Anderson, S.J., Elvidge, C.D. (2009) Paving the planet: impervious surface as proxy measure of the human ecological footprint. *Progress in Physical Geography*. 33: 510-527.
Page 5: Figure 2. European Environment Agency. Accessed from: http://www.eea.europa.eu/data-and-maps/data/eea-fast-track-service-precursor-on-land-monitoring-degree-of-soil-sealing-100m-1
Page 6. Figure 3. European Environment Agency. Accessed from: http://www.eea.europa.eu/data-and-maps/data/eea-fast-track-service-precursor-on-land-monitoring-degree-of-soil-sealing-100m-1
Page 8. Figure 4. Munafò, M., Norero, C., Sabbi, A. and Salvati, L. (2010) Soil Sealing in the Growing City: A Survey in Rome, Italy. *Scottish Geographical Journal*. 126:153-161.
Page 9. Figure 5. Haase, D. (2009) Effects of urbanisation on the water balance – A long-term trajectory. *Environmental Impact Assessment Review* 29: 211-219.
Page 16-18. Figures 6,7,8,9 and Table 1. Haase, D., Nuissl, H. (2007) Does urban sprawl drive changes in the water balance and policy? The case of Leipzig (Germany) 1870–2003 *Landscape and Urban Planning* 80:1-13.
Page 20. Figure 10 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.
Page 22. Figure 11. Yang, B., Li, M-H. (2010) Ecological engineering in a new town development: Drainage design in The Woodlands, Texas *Ecological Engineering* 36: 1639-1650.
Page 26-27. Tables 2,3,4. Marsalek, J., & Schreier, H., (2009) Innovation in Stormwater Management in Canada: The Way Forward. *Water Quality Research Journal of Canada*. 44 (1): v-x.
Page 31. Figure 12. Zhou, X. and Wang, Y-C. (2011) Dynamics of Land Surface Temperature in Response to Land-Use/Cover Change *Geographical Research* 49(1):23-36.
Page 33. Figure 13. Huang, G., Zhou, W., Cadenasso, M.L. (2011) Is everyone hot in the city? Spatial pattern of land surface temperatures, landcover and neighborhood socioeconomic characteristics in Baltimore, MD. *Journal of Environmental Management* 92: 1753-1759.
Page 35. Figure 14. Takebayashi, H., Moriyama, M. (2009) Study on the urban heat island mitigation effect achieved by converting to grass-covered parking *Solar Energy* 83: 1211-1223.
Page 36. Figure 15 and Table 7. Golden, J.S., Carlson, J., Kaloush, K.E., Phelan, P. (2007) A comparative study of the thermal and radiative impacts of photovoltaic canopies on pavement surface temperatures. *Solar Energy* 81: 872-883.
Page 37. Table 8. Santamouris, M., Synnefa, A., Karlessi, T. (2011) Using advanced cool materials in the urban built environment to mitigate heat islands and improve thermal comfort conditions *Solar Energy*. Doi:10.1016/j.solener.2010.12.023.
Page 38. Figures 16,17. Synnefa, A., Karlessi, T., Gaitani, N. (2011) Experimental testing of cool colored thin layer asphalt and estimation of its potential to improve the urban microclimate *Building and Environment* 46: 38-44.
Page 39. Figure 18. Santamouris, M. (2011). Personal correspondence.

About Science for Environment Policy

Science for Environment Policy is a free news and information service from the European Commission's Directorate-General Environment, which provides the latest environmental policy-relevant research findings.

In-depth Reports are a new feature to the service, which report on the latest relevant science for policy issues in question. The service also publishes a weekly News Alert and regular Thematic Issues, which are delivered by email to subscribers and provide accessible summaries of key scientific studies.

For more information or to subscribe to the News Alert and Thematic Issues, please email: sfep@uwe.ac.uk or visit: http://ec.europa.eu/environment/integration/research/newsalert/index_en.htm