

# Chapter 5

## Urban Soil Physics



**Andrew W. Rate**

**Abstract** Urban soils commonly have physical properties which reflect human activity in cities and which affect the functioning of urban soils and the ecosystem services they provide. This chapter starts with presenting some of the physical constraints present in urban soils, such as surface sealing, artificial layering, loss of structure, increased density, and the common presence of coarse fragments. Soil strength is addressed in the context of construction and also soil erosion and slope failure. We also cover the urban heat island phenomenon as it applies to soils in urban environments. The consequences of the sometimes adverse physical properties of urban soils are examined in the context of water-sensitive urban design, soil heating and its consequences, the ‘urban karst’ effect, plant growth, and bearing capacities for buildings and other infrastructure. The final sections cover methods for soil physical measurement in the context of urban environments, starting with standard soil physical measurement techniques and progressing to geophysical and remote sensing methods.

**Keywords** Soil physics · Urban soils · Physical properties · Physical constraints · Impervious surfaces · Soil erosion · Urban heat island · Methods · Geophysical methods

---

A. W. Rate (✉)  
School of Agriculture and Environment, University of Western Australia,  
Crawley, WA, Australia  
e-mail: [andrew.rate@uwa.edu.au](mailto:andrew.rate@uwa.edu.au)

© The Author(s), under exclusive license to Springer Nature  
Switzerland AG 2022  
A. W. Rate (ed.), *Urban Soils*, Progress in Soil Science,  
[https://doi.org/10.1007/978-3-030-87316-5\\_5](https://doi.org/10.1007/978-3-030-87316-5_5)



*What you could learn from this chapter:*

- The various physical constraints which exist in many urban soils.
- How physical constraints affect the delivery of ecosystem services by urban soils and how the same constraints affect suitability of land for engineered structures.
- The range of soil physical parameters that are important for understanding and assessing urban soil environments. An overview of field, laboratory, geophysical, and remotely sensed methods for obtaining soil physical data.

## 5.1 Introduction

In Chap. 4, we covered some of the fundamental physical properties and processes in soils, as they relate to the ecosystem services provided by soils in general. This chapter will discuss common physical constraints on urban soil functions, given the particular physical properties of urban soils introduced in Chaps. 1 and 4. We should remember that urban soils are highly variable, and the physical properties are affected by factors such as the original soil properties and parent material(s), any anthropogenic material added to the soil, soil disturbance, the time elapsed since human modification, climate, and land use.

## 5.2 Physical Constraints Observed in Urban Soils

### 5.2.1 Surface Sealing and Subsoil Layering

The existence of high proportions of land having impervious surfaces, sealed as a result of buildings or paving on the soil surface, is one of the most influential physical features of urban soils (Paul and Meyer 2001; Wong et al. 2012). Since impervious surfaces may cover 60% of cities (Zhu and Carreiro 2004) and may locally be 100% of the land surface (Fletcher et al. 2004), then there are substantial implications for urban soil functioning and ecosystem services. A large proportion of impervious surfaces reduces both shallow and deep infiltration (Fig. 5.1), which is expected to result in lower soil water contents (Coutts et al. 2013) and greatly increase run-off and potentially soil erosion.

A separate but related issue is that of artificial soil layering, which is common in urban soils and is the practice of creating a soil profile with specific properties designed to achieve a desired function. Some examples of artificially layered or *engineered soil profiles* are those in green roofs (Morel et al. 2015) or putting greens on golf courses (USGA 2018). Artificial soil layering may cause impeded water flow and/or shallow *perched water tables* (Jim 1998b). Artificial soil layering may involve abrupt changes in texture and/or density with depth, which will control the downward and upward movement of water and solutes by formation of permeability or capillary barriers (Li et al. 2013).

### 5.2.2 Soil Density and Porosity

The density of soil, measured as the dry bulk density, is commonly greater in urban soils than in natural soils. Dry bulk density greater than 1.6 Mg/m<sup>3</sup> is generally considered to be less suitable for ecosystem functioning, as root growth is restricted (McKenzie et al. 2004). For example, Short et al. (1986a), in urban soils in Washington DC (USA), measured mean soil densities of 1.61 Mg/m<sup>3</sup> in surface soils and 1.74 Mg/m<sup>3</sup> in subsoils, with several values clearly exceeding the 1.6 Mg/m<sup>3</sup> threshold (Table 5.1). Soil bulk density was higher in young urban residential

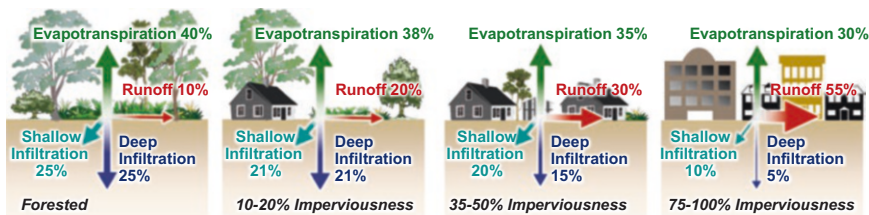


Fig. 5.1 Simplified city-wide water balance at different proportions of impervious surface cover. (Redrawn from USEPA 1993)

**Table 5.1** Bulk density and porosity measurements in urban soils

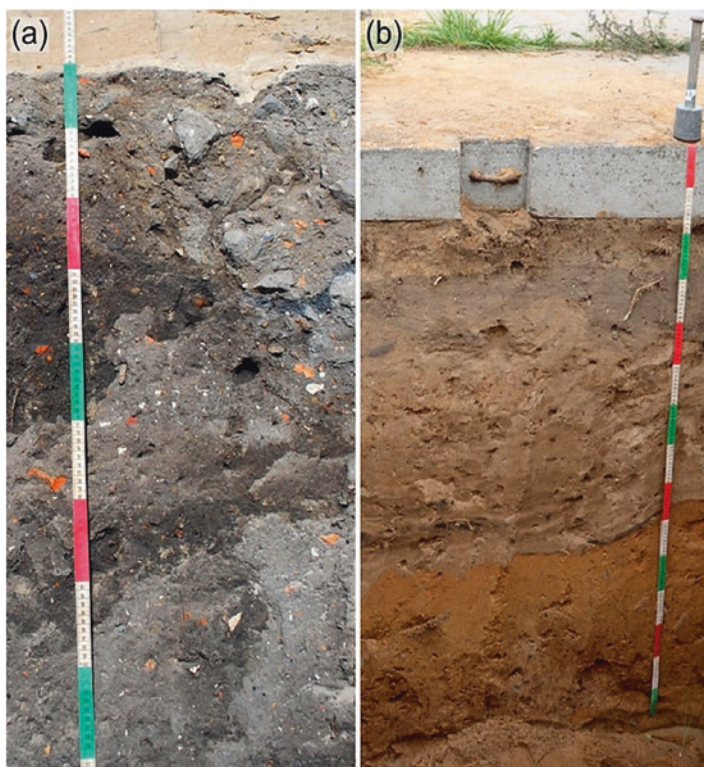
City	Soil depth (cm)	Dry bulk density (Mg/m <sup>3</sup> )		Porosity (vol. %) <sup>a</sup>	References
		Mean	Range		
Hong Kong	10–100 (range of depths)	1.65	1.15–2.63	18.5–57.0	Jim (1998b)
Washington DC, USA	Clods from 0 cm	1.61	1.25–1.85	36.6	Short et al. (1986b)
	Clods from 30 cm	1.74	1.40–2.03	32.8	
Moscow, ID, USA, and Pullman, WA, USA	0–15	–	1.39–1.75	34.0–47.5 <sup>a</sup>	Scharenbroch et al. (2005)

<sup>a</sup>Estimated by the authors, assuming a particle density of 2.65 Mg/m<sup>3</sup>

soils in two urban centres in the USA, with lower densities in older soils; the differences were attributed to pedogenesis (Scharenbroch et al. 2005) but potentially related to confounding differences in texture. The decreased bulk density was not reflected in any changed mean gravimetric soil water content. The porosity of soil is inversely proportional to the bulk density, given similar density of solids (typically ca. 2.6 Mg/m<sup>3</sup>, similar to many silicate minerals (Cresswell et al. 2002)). Urban soils therefore often have relatively low porosity (e.g. some measurements of <20% porosity in Table 5.1), which can affect not only root growth but the movement of water, other liquids, and gases. In many instances, the high bulk density of urban soils may be related to deliberate compaction of soil materials which underlie building or road construction.

### 5.2.3 Coarse Fragments and Artefacts

Many urban soils have large proportions of their volume occupied by coarse (> 2 mm) fragments of anthropogenic origin (as might be expected from the IUSS definitions of some Technosols in Chap. 2, which specify ≥20% coarse fragments of human origin by volume). The presence of large, low-porosity solids in soils (such as natural or anthropogenic stone) results in lower pore volume, as significant porosity only exists between the finer grains. Coarse fragments include components of urban refuse such as construction rubble and household waste. An example of a Technosol with obvious artefact fragments is shown in Fig. 5.2(a); fragments may also include ceramics and, more recently, plastics (El Khalil et al. 2016; Hulisz et al. 2018) (Table 5.2).



**Fig. 5.2** Examples of urban soil profiles showing (a) the content of coarse fragments in an ‘urbic Technosol’ (an urban soil with significant artefact content) and (b) surface sealing in an ‘ekranic Technosol’ (an urban soil having hard material at the surface) (from Hulisz et al. 2018; used with permission from Springer)

**Table 5.2** Types of coarse fragments and artefacts found in urban soils

Study location	Coarse fragments and artefacts	References
Washington, DC, USA	Brick, concrete, nails (iron), glass	Short et al. (1986b)
Hong Kong, China	Stones (building rubble, other foreign substances)	Jim (1998b)
Hong Kong, China	Stones (granitic fill, shells)	Jim (1998a)
Moscow, Russia	Construction wastes, stones, brick debris, cement, concrete, metallic materials, wood, nutshells, leather	Alexandrovskaia and Alexandrovskiy (2000)
Marrakech, Morocco	Bones, fabrics, glass, metal, plastic, wood	El Khalil et al. (2016)
Toruń and Zielona Góra, Poland	Gravel, concrete, bricks, cinder, metals, ceramics, plastic, bones, glass, charcoals	Hulisz et al. (2018)

### 5.2.4 *Soil Structure*

Urban soils are typically poorly structured in their early stages of development. Soil aggregation to form structural elements (peds) occurs progressively along with other soil formation processes. Many urban soils are developed on soil materials modified or created by human activity and so are relatively young, with minimal change due to pedogenesis – including minimal development of soil structure (Jim 1998b; Chen et al. 2014). The development of soil structure is one of the mechanisms that increases soil porosity, provided that the soil materials have suitable properties (e.g. sufficient clay content – see White 2006). The high bulk density and corresponding low porosity of many urban soils (Table 5.1) can be another consequence of the limited development of structure, or processes such as compaction and disturbance may cause both the lack of structure and the low porosity (high density).

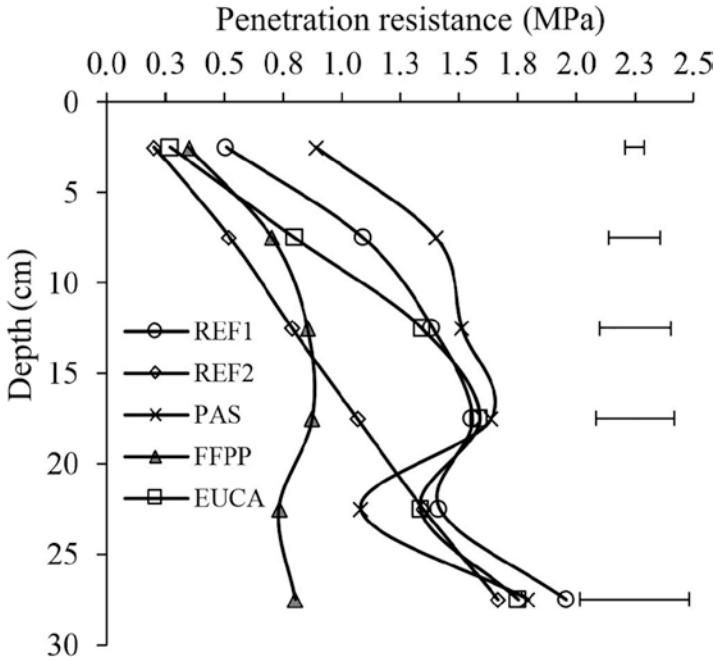
Improvements in urban soil structure may result from amendment of soils with composts made from urban waste materials. Fourvel et al. (2019) studied the effect of green waste compost on soil and dredged dam sediment, finding that compost improved the structural parameters of the soil materials. Increases in mean weight diameter of soil aggregates (i.e. better structure), decreases in bulk density, and increases in macroporosity persisted for up to 18 months following compost addition to the soil materials. Structural improvements can also be achieved using organic materials from other waste streams, such as biosolids (digested sewage sludge) (Kumar and Hundal 2016). Dredged dam sediments can provide a potentially fertile material to offset soil loss in urban environments, and their amendment with organic waste materials therefore represents beneficial reuse of both materials (Almeida et al. 2001), although dredged materials may contain potentially acidifying sulphides.

### 5.2.5 *Soil Strength*

Soil strength is important in different ways depending on the context. For maintenance of a biological community, high soil strength is undesirable, but in the context of preventing erosion or slope failure or supporting built infrastructure, high soil strength is advantageous.

Soils with high strength are common in urban environments, and this is frequently a consequence of deliberate or accidental soil compaction. Only a few studies have measured soil strength, for example, in terms of penetration resistance, in urban environments. For example, Chatterjea (2007) found significantly higher penetration resistance on and around walking trails in an urban park in Singapore, with on-trail penetration resistance frequently  $\geq 1$  MPa. The increased resistance to penetration in Chatterjea's (2007) study was related to the compaction caused by human foot traffic. Rocha et al. (2015) also measured high penetration resistance in soils being rehabilitated to forest in a peri-urban environment in Brazil (Fig. 5.3).





**Fig. 5.3** Variation of penetration resistance with depth in soils being rehabilitated to forest in Garça city, Sao Paulo, Brazil. REF1 and REF2 refer to sites reforested with Brazilian native tree species; PAS is a site under pasture; FFPP is a remnant forest site (control); and EUCA is planted with *Eucalyptus* species. Translated version redrawn from Rocha et al. (2015) and used under the conditions of a CC-BY-4.0 licence

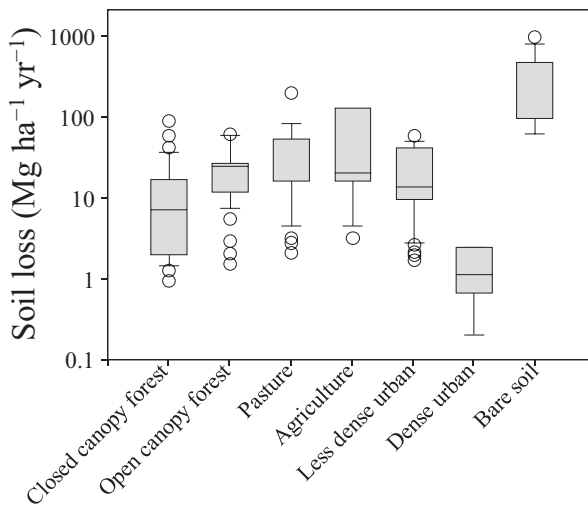
### 5.2.6 Soil Erosion and Erodibility

It has been known for some time that urbanisation causes local increases in soil erosion, for example, due to construction of buildings and roads exposing bare soil. Erosion is exacerbated by the increased volume and velocity of run-off from impermeable surfaces. The increased sediment yield from erosion of urban soils generally has the consequence of increased sediment load of urban streams (Wolman and Schick 1967). The short-term rates of erosion in terms of soil depth with time can be up to 18 cm/year on soil materials exposed or deposited by construction practices. For individual projects, therefore, soil erosion is a crucial consideration (Rowlands 2018).

Less severe water erosion is usually in the form of sheet (or sheetwash) and rill erosion (Fig. 5.4), caused by water flowing over unconsolidated land surfaces such as bare soil or with minimal vegetation cover (Knox et al. 2000). Soil loss by sheet and rill erosion is dependent on rainfall intensity and landscape factors such as slope steepness, slope length, and vegetation or impermeable cover. Soil factors also affect soil loss by water erosion; a soil’s intrinsic erodibility depends on properties



**Fig. 5.4** Sheet and rill erosion of bare soil on a slope exposed by urban construction activities. (Photograph by Andrew W. Rate)



**Fig. 5.5** Soil loss by erosion for different land use types in Puerto Rico. Redrawn from Del Mar López et al. (1998); used with permission from the College of Arts and Sciences, University of Puerto Rico, Mayagüez

like soil structure and texture, organic matter content, hydraulic conductivity, and soil strength (White 2006).

On a larger scale, therefore, urban soil erosion may be lower than for other land uses, because on average the land surface is covered with either vegetation (e.g. lawns) or impermeable surfaces that protect the soil surface from rainwater impact (Del Mar López et al. 1998; Knox et al. 2000) (Fig. 5.5). Del Mar López et al. (1998) modelled erosion with the Revised Universal Soil Loss Equation (RUSLE2; see Box 5.1) and assumed that the ‘crop factor’ (i.e. protection of land by vegetation



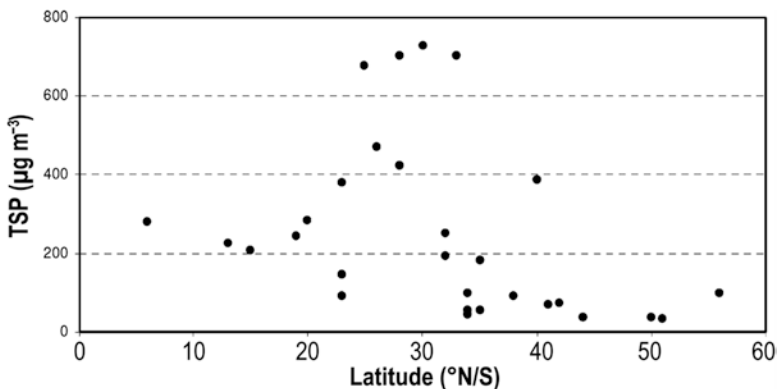
cover) was more protective for densely developed urban land than for any other land use category, including closed-canopy forest. Even though vulnerable soil in urban environments is far more erodible than in rural settings (Wolman and Schick 1967; USDA 2000), the overall effect of surface sealing in urban areas can be to decrease erosion relative to natural environments on a whole-city scale (Fig. 5.5).

The erosion of soil from urban environments may still exceed erosion from other land use types such as forest or agriculture, especially when rapid urbanisation is occurring (e.g. see Erskine et al. 2003; Martin et al. 2003; Ozsoy and Aksoy 2015).

### Wind Erosion

Erosion of particles from soils by wind in arid and semi-arid environments can be a significant pathway for soil loss. For example, Khresat et al. (1998) recognised urban expansion as a contributor to desertification in Jordan, with some of the most important mechanisms being erosion by water and wind. Urban soil erosion is also a significant source of airborne particulate matter (Eliasson et al. 2008) (Fig. 5.6), which may have adverse effects on human health. Although the source of some soil particles in air is external to urban centres, some studies show greater particulate concentrations in city centres compared with peri-urban areas (Eliasson et al. 2008).

Urban development has been a contributing factor in catastrophic landslides. For example, the 1979 Abbotsford landslide in New Zealand (Fig. 5.7), involving ca.  $5 \times 10^6 \text{ m}^3$  of soil and underlying unconsolidated sediment, was caused by multiple natural and urban factors. Natural factors included the slope of  $7\text{--}10^\circ$  along sediment bedding planes and soil and underlying material containing smectite clay with very low shear strength. The factors related to urbanisation which were identified included excavation of material on the lower slope, a leaking water main pipe that increased pore water pressure, and minor contributions from the increased mass of buildings and paved areas and removal of vegetation (Hancox 2008).



**Fig. 5.6** Daily mean total suspended particulates (TSP,  $\mu\text{g m}^{-3}$ ) in urban air for different cities, as a function of latitude ( $^\circ\text{N}$  or  $^\circ\text{S}$ ). (From Eliasson et al. 2008; used with permission from Springer)



**Fig. 5.7** Catastrophic slope failure in suburban Abbotsford, New Zealand, 1979. (Image from Hancox 2008; used with permission from Springer)

### Box 5.1 The Revised Universal Soil Loss Equation

The Revised Universal Soil Loss Equation (RUSLE) predicts soil loss by water erosion and has been modified several times since the original USLE was developed by Walt Wischmeier at the US Department of Agriculture in the 1960s. The USLE model was originally intended for predicting soil losses from croplands in the USA and was updated for prediction in other environments, such as constructed areas, in 1978 (Renard et al. 1997). The latest version, RUSLE2, is based on the following equation (Foster et al. 2003):

$$A = S \sum (r_i k_i l_i c_i p_i)$$

where:

$A$  is the average annual erosion

$r$  is the rainfall/run-off erosivity factor

$k$  is the soil erodibility factor

$l$  is the topographic factor (slope steepness, roughness, etc.)

$c$  is the cover-management factor

$p$  is the support practices factor

and the subscript  $i$  denotes the daily index value for each factor ( $r$ ,  $k$ ,  $l$ ,  $c$ ,  $p$ )

RUSLE2 multiplies the daily factor values to estimate daily erosion values, which are summed (indicated by the  $\sum$  symbol in the equation) for all days in a year to estimate average annual erosion. Previous versions of RUSLE included the  $k$  and  $c$  factors varying with time but not all factors as in RUSLE2.

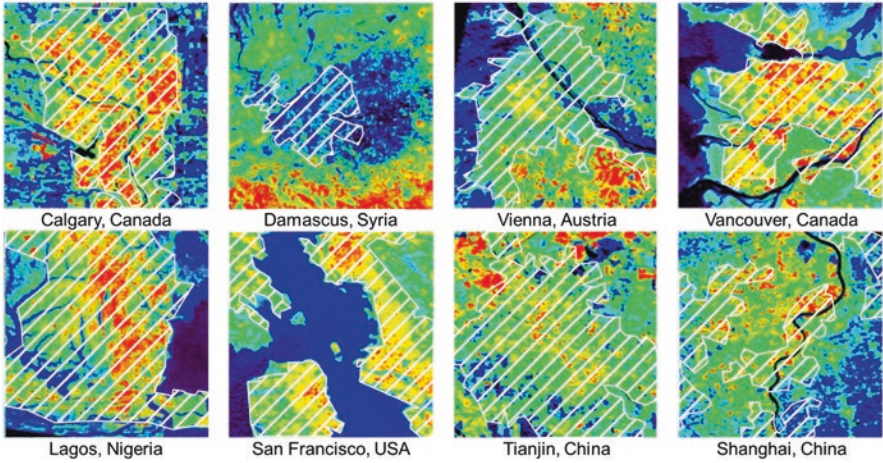
There are fewer applications of the USLE or RUSLE to soil loss by erosion of urban soils than for agricultural soils, possibly as the model assumptions are not fulfilled. More advanced modelling approaches such as the USDA's Water Erosion Prediction Project (WEPP) may offer more reliable prediction (Lafflen and Flanagan 2013).

### 5.2.7 Soil Temperature and Heat Fluxes

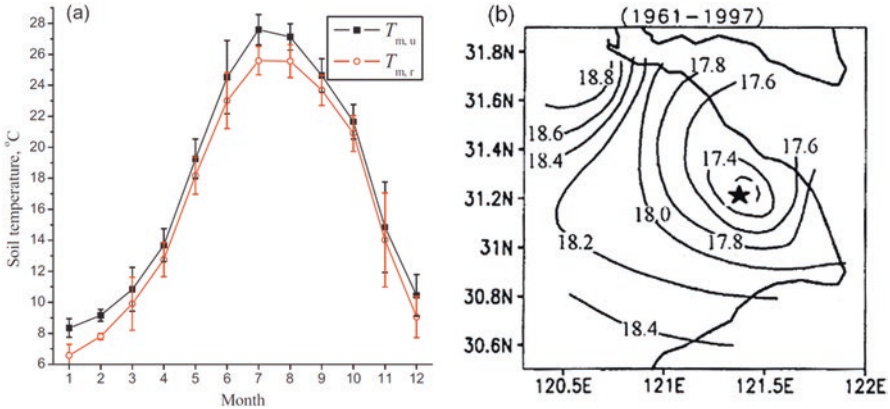
The *urban heat island* effect is the tendency of urban areas to have greater air and land surface temperatures than the surrounding peri-urban and rural areas. Urban heat islands have been known to exist since the early 1800s and have been confirmed by numerous studies using micrometeorological and remote sensing techniques over the last 40–50 years (Landsberg and Maisel 1972; Hafner and Kidder 1999; Small 2006; Min et al. 2019). There are multiple potential causes of urban heating, including the abundance of impermeable surfaces with large heat capacities and low reflectivity, intentional release of heat from combustion, the low proportions of vegetated land and open water which would otherwise confer an evaporative cooling effect, and lower soil water contents requiring less heat input for evaporation from soil. The increased surface area and heat capacity of tall buildings create the so-called canyon effect which is known to cause additional urban heating (Landsberg and Maisel 1972; Changnon 1999; Grimm et al. 2008; Tang et al. 2011). Examples of surface temperature gradients in and around several urban areas are shown in Fig. 5.8, showing that urban heat island effects are widespread, but they do not occur in all cities.

The greater air and land surface temperatures in urban areas would logically lead to greater soil temperatures, and this is generally supported by measurements. Changnon (1999) used a 60-year time series of air and soil temperature data in Champaign, Illinois, USA, to show an increasing trend attributed to urbanisation. A similar soil temperature increase was confirmed by Savva et al. (2010) who measured increases in soil temperature under both turf grass and urban forest in Baltimore, USA. Based on depth profiles from geothermal boreholes in Gateshead, UK, Banks et al. (2009) presented evidence that soil heat fluxes from an urban heat island had warmed surface soil and underlying sedimentary rocks to a depth of at least 55 m. Finally, in an extensive study in Nanjing, China, Tang et al. (2011) measured differences in urban and rural soil temperatures of between 1 and 3 °C (Fig. 5.9a). The city of Shanghai, China, however has an urban heat island only in terms of air temperature, whereas soils in the urban centre of Shanghai are cooler than soils in surrounding suburbs, a phenomenon which is likely to be due to increased shading (Fig. 5.9b).

The greater soil temperature in urban systems, caused by greater heat fluxes from atmosphere to soil, would need to be at least partly balanced by greater outgoing heat fluxes. Some of this heat loss flux would be soil heat flux to deeper soil, including to considerable depths, as suggested by Banks et al. (2009). Soil evaporation (latent heat flux), however, would also be likely to increase, resulting in drier urban



**Fig. 5.8** Urban heat island effects shown by images derived from analyses of Landsat ETM+ spectra. Approximate urban extents (from Google Maps and shown as white cross-hatched polygons) are superimposed on surface temperature images selected from Small (2006) and used with permission from Elsevier. Colour scale in temperature maps ranges from black and blue tones (cooler) to red tones (warmer)



**Fig. 5.9** (a) Yearly trend of urban ( $T_{m,u}$ ) and rural ( $T_{m,r}$ ) mean soil temperatures (from Tang et al. 2011) and used with permission from Elsevier; (b) urban ‘cool island’ of surface soil temperature in Shanghai, China (from Chen et al. 2003), with contours in °C and the ★ symbol representing the urban centre (used with permission from Springer)

soils. Greater soil temperature would also be expected to affect soil chemical and biological processes (such as faster chemical reactions or greater microbial activity when soil water content is sufficient; for more detail see Xiao et al. (2005) and Peters and McFadden (2010)).

Soils are important for regulation of urban microclimates (Mao et al. 2014). The ability of urban soil to cool the overlying atmosphere by way of the latent heat flux will clearly be lower for drier soils, however, since the latent heat flux represents the heat content of evaporating water vapour (Coutts et al. 2013). Urban vegetation, especially trees, promotes cooler soils by providing shade and by allowing greater evapotranspiration (i.e. latent heat flux) from soil (indirectly) to the atmosphere (Lin and Lin 2010).

### **5.2.8 Heterogeneity of Soil Physical Properties**

Although this issue has already been addressed in Chap. 3, it is worth remembering that substantial short-scale heterogeneity in soil physical properties can exist in both anthropogenic and ‘natural’ soils. One example is the artificial layering discussed briefly in Sect. 5.2.1. There have not been many researchers who have studied short-range variability of soil physical properties, but it is an important issue to consider for engineering properties of soils and may require an additional margin of safety to be applied, for example, in the case of load-bearing soils for construction (Uzielli et al. 2006).

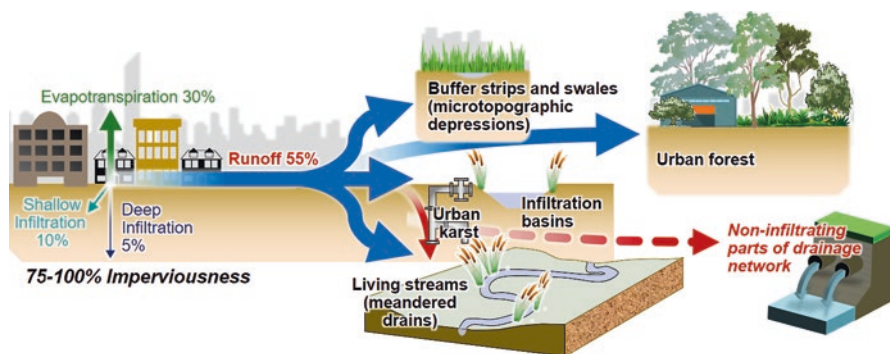
## **5.3 Effects of Urban Soil Physical Constraints on Ecosystem Functioning**

### **5.3.1 Effect of Impervious Surfaces**

Lower infiltration of water into a landscape with high impervious surface cover (Paul and Meyer 2001) can be assumed to result in less soil water being available for plants and soil biota (Coutts et al. 2013). Some studies, however, have found that changing the permeability of surface cover has little to no effect on the growth of urban trees (Morgenroth and Buchan 2009; Volder et al. 2009). The transfer of water to soils, and consequent availability of water to plants, in urban environments can be increased with *water-sensitive urban design* (WSUD) features such as swales and buffer strips or rain gardens (Fig. 5.10).

Impervious surfaces also differ from pervious surfaces or uncovered soil in their thermal characteristics. For example, Montague and Kjelogren (2004) showed that the albedo of different surface materials decreased in the order: concrete > gravel rock mulch > turf > asphalt > pine bark mulch > lava rock mulch. In the same study, thermal conductivity decreased in a somewhat different order: asphalt > concrete > turf > gravel rock mulch > pine bark mulch > lava rock mulch. Both low albedo and high thermal conductivity would be expected to result in greater temperatures in the



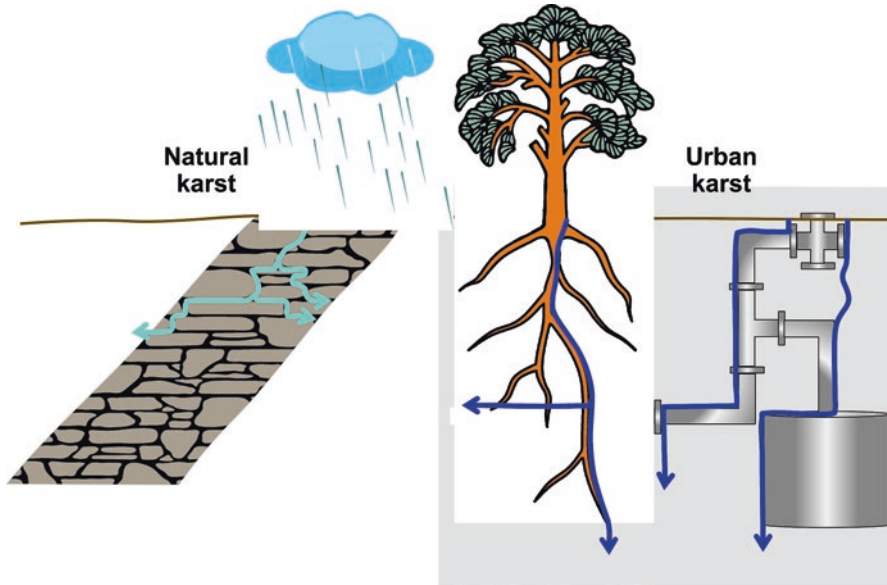


**Fig. 5.10** Modified version of part of the ‘classic’ urban water balance diagram in Fig. 5.1, showing some possible pathways based on water-sensitive urban design for the increased run-off generated by high proportions of impervious surfaces. (Graphic by Andrew W. Rate)

underlying soils, but actual observations were only partly consistent with this expectation. Under all net solar radiation scenarios, the greatest soil temperatures were under asphalt and concrete, with the lowest soil temperatures under pine bark mulch (Montague and Kjelgren 2004).

Deliberately buried infrastructure, such as pipework for urban utilities, has the same effect as coarse fragments in reducing the effective soil volume for ecosystem services, like water storage and water and solute movement. Some authors call this the *urban karst* effect, and the phenomenon is illustrated in Fig. 5.11). This is because of the combined effects of limited infiltration areas from impervious surface cover, underground cavities, buried infrastructure, and tree roots creating *preferential flow* pathways in the same ways as natural ‘karst’ landscapes formed by dissolution-dominated weathering of limestones (Gwenzi and Nyamadzawo 2014; Bonneau et al. 2017). Urban impervious surfaces create more focused areas for water infiltration (sometimes in intentionally constructed basins) which increases percolation of water into discrete smaller areas, even leading to local mounding of groundwater. Installation of buried infrastructure such as pipework with smooth surfaces, and infilling of infrastructure trenches with high-permeability materials such as coarse sands and gravels, creates preferential flow pathways for water and solutes within urban soils (Bonneau et al. 2017). An important combined outcome of localised infiltration and preferential water flow in urban soils is therefore to, in some cases, increase leaching of substances dissolved in water. These substances may be contaminants such as nutrients, metals, organic compounds, or pathogens; the preferential flow means less interaction with the solid materials in the soil, consequent greater concentrations in pore water, and therefore possible groundwater contamination.





**Fig. 5.11** The urban karst phenomenon, showing a schematic of preferential water flow (arrows) through natural fractured limestone karst at left and at right preferential flow along the boundary of soil with tree roots or buried infrastructure in an urban karst. (Graphic by Andrew W. Rate, inspired by US EPA (1993))

### 5.3.2 *Effects of Soil Density and Porosity*

Bulk density greater than ca.  $1.6 \text{ Mg/m}^3$  is usually considered to be undesirable (McKenzie et al. 2004). The actual threshold bulk density value is dependent on texture (see US EPA 2011), and the upper threshold value may be as high as  $1.8 \text{ Mg/m}^3$  before plant growth is severely restricted on sandy soils. The total porosity of soil is best understood in the context of air- and water-filled pores; air-filled porosity needs to be ca. 10% of total soil volume at field capacity water content for adequate aeration for plants and aerobic microorganisms (Hazelton and Murphy 2011). Low porosity confers a greater risk of inadequate air-filled porosity in wet soils, with consequent risks of waterlogging and anoxia (White (2006) suggests a minimum porosity of 23% by volume – have another look at Table 5.1). High water-filled pore space can decrease soil strength; low porosity, especially the absence of macropores, causes low infiltration rates resulting in run-off and potentially soil erosion.

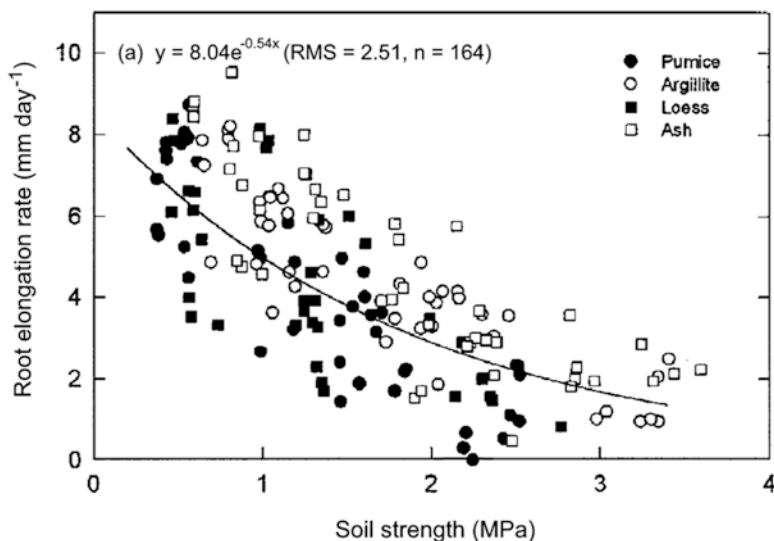
### 5.3.3 Effects of Soil Strength

#### 5.3.3.1 Effects on Biological Components of Soil

Plant root growth decreases with increasing soil strength (see Fig. 5.12 and Zou et al. (2001)). Hazelton and Murphy (2011) state that root growth will be severely restricted for cereal crops at penetration resistance  $\geq 2\text{--}2.4$  MPa, since roots can only explore pre-existing pores and planes of weakness in a soil. Soil shear strength limits root elongation at 70 kPa in sandy loam soils, and up to 290 kPa in clays (see Hazelton and Murphy 2011, who also present limiting values of soil shear strength for germination, ‘coleoptile elongation’, and seedling emergence).

#### 5.3.3.2 Effects on Human Construction

Typical bearing capacities for a range of soils and soil-like materials range from  $<75$  kPa for soft clays and silts to  $\geq 300$  kPa for compacted sand and up to  $>600$  kPa for dense gravel (or sand plus gravel) (Geotechdata.info 2015). Some typical values of bearing limits for urban soils and related materials are presented in Table 5.3. These values have a safety factor applied; if soil has insufficient bearing capacity for the weight of structure, shear failure of the soil beneath and adjacent to foundations can compromise the built structure. The dependence of shear strength on grain size and morphology means that soil strength can be increased by mixing with a coarse-grained material such as rock chips (Rahardjo et al. 2008).



**Fig. 5.12** Effect of soil strength (MPa) measured by penetration resistance on root growth (mm day<sup>-1</sup>) of *Pinus radiata* seedlings (Zou et al. 2001; used with permission from Springer)

**Table 5.3** Bearing limits of earth materials based on shear strength. (British Standards Institution 1986)

Material	Bearing limit (kN/m <sup>2</sup> )
<b>Rocks</b>	
Strong unweathered igneous or gneissic rock	10,000
Strong unweathered limestones or sandstones	4000
Unweathered schists and slates	3000
Strong unweathered shales, mudstones, or siltstones	2000
<b>Soils</b>	
Dense gravel/dense sand plus gravel	> 600
Medium dense gravel/medium dense sand plus gravel	< 200–600
Loose gravel/loose sand plus gravel	< 200
Compact sand	> 300
Medium dense sand	100–300
Loose sand <sup>a</sup>	< 100
Very stiff boulder clays and hard clays <sup>b</sup>	300–600
Stiff clays <sup>b</sup>	150–300
Firm clays <sup>b</sup>	75–150
Soft clays and silts <sup>b</sup>	< 75

<sup>a</sup>Depends on degree of looseness; <sup>b</sup>susceptible to long-term settling/compaction

Soil compressibility is also an issue, measured by a range of parameters (e.g. bulk modulus, volumetric compressibility) depending on the context (e.g. whether the soil is laterally constrained; see Terzaghi et al. 1996; Liu and Evett 2008). Coarser materials such as gravels and sands tend to have lower compressibility and are therefore more suitable for construction than more compressible silts, clays, and organic-rich soils for which settlement can be a severe problem.

In extreme cases, urban development may lead to potentially dangerous or even catastrophic events such as large sinkholes (Fig. 5.13) or landslides. The sinkhole which formed in Harbor, Oregon, USA, shown in Fig. 5.13 was along the line of a stream gully which had been infilled to allow construction. Preferential flow of water down the path of the former stream during heavy rain resulted in tunnel erosion, with the sinkhole forming as the material overlying the tunnel collapsed. Julian and Anthony (1996) discuss the increased incidence of landslides related to coastal urban development in south-eastern France, noting that human activities such as mechanical compaction, road construction, and removal of vegetation are factors contributing to slope failures.



**Fig. 5.13** A large sinkhole which formed in Harbor, Oregon, USA, in 2016, probably caused by preferential subsurface water flow down an infilled former valley (from upper right to lower left of image (c)) during heavy rainfall (Photo credits: (a, b), Oregon Department of Transportation, used under terms of Creative Commons Attribution 2.0 Generic license; (c) still from YouTube video by Kyle Rice, Triook Technology, Harbor, Oregon, USA (used with permission))

### 5.3.4 *Effects of Soil Erosion*

Erosion of urban soils, especially during the construction phases of urban development, is a significant source of sediment to streams and rivers (Paul and Meyer 2001) and ultimately to the marine environment (USEPA 1993). The ecology of urban streams can be affected significantly by increased sediment load, resulting in effects such as eutrophication, reduced biodiversity of plants and invertebrates, and reduced diversity and population declines for fish species (Paul and Meyer 2001). Export of sediment to streams by soil erosion is also associated with stream sediment contamination (Sutherland 2000). In stormwater drainage systems, excessive sedimentation from soil erosion may necessitate drain maintenance by excavation of drain sediments (Department of Environment 2004).

Wind erosion of soil (including urban soil) increases the concentration of fine particles suspended in the atmosphere (Chan et al. 2008; Eliasson et al. 2008;

Athanasopoulou et al. 2010). Erosion by wind is particularly relevant in drier soil environments, which in urban environments may result from higher soil temperatures and reduced deep and shallow infiltration due to impervious surfaces. The combined influences of both the urban heat island effect, and the increasing temperature trend due to climate change, may result in increasing severity of wind (*aeolian*) erosion of urban soils.

Erosion of surface soils by water and wind also represents a loss of fertility due to the vertical stratification of nutrients and soil organic matter, in that the greatest concentrations of nutrients and organic matter are at or near the soil surface. Establishment of vegetation may therefore be more difficult (e.g. in rehabilitation of urban soils) if erosion occurs, unless soil amendments are used to manage fertility (US EPA 2011).

### 5.3.5 *Effects of Warmer Soils*

Since (with some exceptions, such as Damascus, Lebanon (Fig. 5.8), or Shanghai, China (Fig. 5.9)) urban soils are likely to be warmer than their natural soil counterparts, it is worthwhile considering the effects of greater soil temperature on soil processes and functions.

Warmer soils will tend to be drier; the lower water content is driven by external energy inputs which are balanced by the latent heat flux of the soil (Hillel 2014; see Chap. 4). The theory is consistent with measurements in urban soil systems; for example, Wang et al. (2011) measured greater evapotranspiration by urban trees at higher soil temperatures. Evaporation of water directly from soil also requires there to be a relative humidity gradient between soil and the atmosphere, however, so warm soils will not always dry out.

Combined warming and drying of soil will generally cause decreases in biological activity. Plants will experience water stress (Hillel 2014), and soil microorganisms from urban soils may not survive extreme drying (Gleason et al. 2004). In some cases, though, soil microorganisms may adapt to the selection pressure applied by higher temperatures so that they can better survive warming and/or drying (McLean et al. 2005).

At greater soil temperatures in the absence of water limitation, microbial processes occur more quickly. The most obvious example is that of soil organic matter decomposition, commonly measured as respiration of CO<sub>2</sub> by soils. In urban soils in Auckland, New Zealand, Weissert et al. (2016) showed that soil temperature and soil water content were the best predictors of soil CO<sub>2</sub> emissions across a range of land uses and soil types, including urban parks and areas of remnant and planted forest. Other microbially driven processes have also been shown to respond to temperature changes in urban soils. Methane emissions from urban wetland soils (which are driven by microbial processes) in Ohio, USA, increased with increasing soil temperature (Morin et al. 2014). Similarly, the net mineralisation of nitrogen, another process dominated by soil microbial and mesofaunal activity, was greater in

urban than rural environments, an effect attributed to an urban heat island (Pavao-Zuckerman and Coleman 2005).

Plant growth can also be affected by increased soil temperature in urban environments. Ziska et al. (2004) found that plant productivity was more closely related to soil temperature than to daytime air temperature or atmospheric CO<sub>2</sub> concentration, along a rural-urban gradient in Maryland, USA (the study ensured that soil water content or nutrients were not limiting factors to plant growth).

## 5.4 Soil Physical Measurements

### 5.4.1 *Standard Soil Physical Methods*

There are numerous standard field and laboratory-based methods for determining soil physical properties, and it is not our intention to review these comprehensively in this textbook. We will include a brief discussion below and refer readers to excellent compilations of soil physical methods in Cresswell et al. (2002) and Dane and Clarke Topp (2002).

There are numerous soil physical parameters which are important to be measured or estimated in urban soils. It is useful to have information on basic soil properties such as density, porosity, coarse fragments, water content, soil texture, soil structure, soil temperature, and electrical conductivity.

Parameterised models can be used to estimate or predict soil physical parameters which are difficult to measure. These may be *mechanistic*, meaning that the model is based on a theoretical understanding of the processes involved, such as the equation describing a soil water retention curve using the van Genuchten equation (e.g. see de Lima et al. 2016). Alternatively it is sometimes possible to predict the values of soil properties because they are statistically related to other (more easily measurable) soil properties, without assuming any physical mechanism. The statistical relationships are usually regression models (see Chap. 3), giving rise to the so-called pedotransfer functions, which are used to predict soil physical parameters that are difficult to measure (Cresswell et al. 2002, Chap. 22). (Table 5.4)

### 5.4.2 *Geophysical Methods*

A number of ‘geophysical’ techniques have the potential to generate two- or three-dimensional representations of the below-ground soil environment and therefore to provide information which include soil variability across a landscape and/or with depth. They can be especially useful in combination with each other, to cross-validate detection of subsurface soil features and properties. The soil properties accessible by geophysical methods are, not surprisingly, mainly soil physical



**Table 5.4** Examples and availability of methods for determining soil physical properties in the field and laboratory

Soil physical property	In situ/field method	Laboratory method
Soil depth	Excavation; push-probe	–
Water table height	Piezometers, bores	–
Bulk density	Water replacement and related methods, neutron probe	Volumetric/gravimetric on undisturbed field cores
Coarse fragments	Sieving/gravimetric	Sieving/gravimetric
Water content	Time domain reflectometry (TDR), neutron probe	Thermogravimetric
Water potential	Tensiometers	Filter paper method
Water repellence	–	Molarity of ethanol droplet (MED) test
Texture	Manual deformation	Gravitational sedimentation
Structure	Field observation	–
Aggregate stability	Emerson test (qualitative)	Wet sieving
Penetration resistance	Field penetrometer	Penetrometer
Shear strength	–	Triaxial cell; direct shear box
Compressibility	–	Consolidometer; triaxial compression cell
Water retention curve	Simultaneous TDR or neutron probe + tensiometers	Pressure plates/tables, plus gravimetric
Infiltration rate	Double-ring or tension infiltrometer, well permeameter	–
Hydraulic conductivity	Depthwise soil pore water samplers or thermistors	Constant- or falling-head permeameters
Soil temperature	Thermocouples; thermistors	–
Heat fluxes: Latent and sensible	Eddy covariance; Bowen ratio method	–
Electrical conductivity/resistivity	Suspension and field conductivity meter; EM survey; electrical resistance tomography	Suspension and conductivity cell
Particle density	–	Volumetric/gravimetric
Specific surface area	–	BET sorptimetry
Atterberg limits	–	Drop-cone penetrometer + thermogravimetric
Evapo(transpi)ration	Lysimeters; plant-based techniques	–
Air permeability	Surface-chamber method	Manometer/flow meter
Heat capacity, soil heat flux	Dual-probe heat-pulse method	Dual-probe heat-pulse method
Thermal conductivity	Time series of depthwise temperature gradient	Time series of depthwise temperature gradient
Solute transport (esp. models)	Lysimeters; soil pore water samplers; groundwater tracers	Hydrogeochemical simulation models; lysimeters

Source: Cresswell et al. (2002), Dane and Clarke Topp (2002)

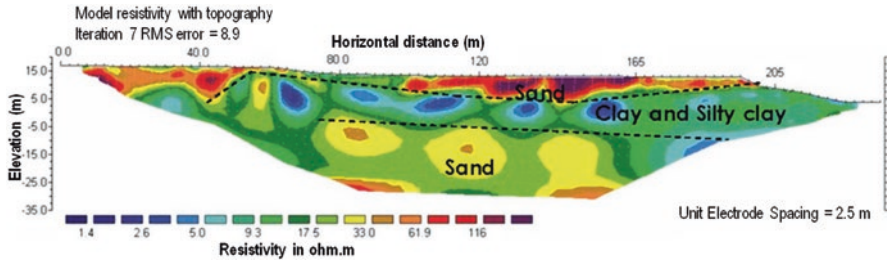
properties (sometimes modified by chemical composition parameters such as salinity). Chemical and biological soil properties are not generally able to be determined by above-ground probes such as those described below and are dependent on physical sampling and subsequent laboratory analyses.

*Ground-penetrating radar (GPR)* is based on detection of the rate of propagation and strength of reflection of a pulse of radiofrequency electromagnetic radiation applied at the soil surface. It has been used to measure soil depth to bedrock and detect voids and buried infrastructure in urban contexts (Saarenketo and Scullion 2000), in situ urban tree root morphology (Stokes et al. 2002), as well as in archaeological exploration of ancient cities (Leopold et al. 2011).

*Magnetic methods* include magnetic gradiometry (i.e. measurements of magnetic field gradient) and magnetic susceptibility. For example, Magiera et al. (2006) measured magnetic susceptibility on a ca. 10 km grid spacing in surface soils across Poland, the Czech Republic, and Germany, finding that urban soils had a distinct magnetic signature. Similarly, magnetic gradiometry was used in Montréal, Canada, to assess the subsurface of landfill soils, in combination with other geophysical techniques (Boudreault et al. 2010). Like other methods, magnetic gradiometry is also used in urban archaeology (e.g. see Boschi (2012), and the examples in Chap. 2).

*Electrical resistivity/conductivity* of the subsurface is the basis for geophysical techniques such as electromagnetic (EM) mapping and electrical resistivity tomography (ERT). The simplest and most portable method is EM mapping, with handheld and vehicle-mounted instruments available. Examples of the use of EM mapping in urban soils include detection of buried infrastructure at a decommissioned coal mine in Lünen, Germany (Bell and Failey 1991) and mapping of various underground utilities (e.g. pipes, tanks) in Jeddah City, Saudi Arabia, in combination with GPR (Rashed and Atef 2015). The investigation by Rashed and Atef (2015) also utilised the ability of EM methods to provide magnetic susceptibility data, allowing discrimination of different materials (plastics, metals).

Electrical resistivity tomography is a more complex technique, logistically, in terms of numerical processing requiring inverse modelling of raw data but importantly with respect to the additional information provided. It relies on acquisition of data, over typical time frames of 0.5 to a few hours, from linear electrode arrays inserted into surface soil. The type of information provided by ERT typically relates to soil water content and soil texture, since both affect the electrical conductivity of the subsurface. An example of the use of ERT in an urban soil environment was to assess land suitability for potential urban or tourism development near the urban area of As Siliyin, El-Fayoum, Egypt (Metwaly, 2010 #5646; see also Fig. 5.14). The ERT information collected by Metwaly et al. (2010) was used to discriminate sediment textures and water content, to help understand the groundwater resource at the site (Fig. 5.14). Boudreault et al. (2010) showed that ERT also has the capability to detect solid, high-resistivity zones and objects in urban soil-like materials. An archaeological application of EM and ERT in cities, to locate previously unknown bronze production sites in Athens, Greece, is described by Leopold et al. (2011).



**Fig. 5.14** Electrical resistivity tomography inversion image for a cross section in the peri-urban area of As Siliyin, Egypt (30.793 E, 29.381 N). (Image from Metwaly et al. (2010); used with permission from Springer)

It is worth mentioning *seismic geophysical techniques*, because as well as providing in situ information about the subsurface environment, they can provide estimates of the risks posed by earthquakes, as well as minor seismic phenomena such as vibrations from heavy vehicles and construction activities. An application of surface-based, non-destructive seismic methods for soils and volcanic sediments with a range of consolidation is described for the urban environment of Napoli, Italy, by Nunziata et al. (2004).

*Other geophysical techniques* include (but are not limited to) *induced polarisation*, which is related to ERT but measures the ability of different subsurface materials to hold an electrical charge (e.g. Cardarelli and Di Filippo 2004), and magnetic resonance sounding, which can yield information about free water content and hydraulic conductivity (e.g. Lubczynski and Roy 2003). Both techniques are used down pre-existing boreholes through soil and underlying material, and induced polarisation can also be used in linear electrode arrays in the same way as ERT.

### 5.4.3 Remote Sensing Methods

Remotely sensed data, using imagery from satellites or aircraft, have been used for many years to assess urban environments, including collection of data on urban soils. Many landform or land use parameters, and soil physical properties, are accessible by remote sensing. Only a few soil chemical and biological properties are accessible using remote sensing methods.

*Satellite data.* In an early example, Ormsby (1982) used Landsat 3 visible, near-infrared, and thermal data to discriminate selected pairs of land covers including urban vs. agricultural or urban vs. unvegetated/extractive industry land. More recent investigations using Landsat data are based on fitting remotely sensed imagery to the vegetation – impervious surface – soil (V-I-S) model (e.g. Phinn et al. 2002; Wu and Murray 2003), with an important outcome being reliable estimation of impervious surface cover in cities. Other satellite-derived data, such as MODIS or ATLAS, have been used to map various parameters relevant to urban soil environments,

including soil temperatures and urban heat island effects (Schneider et al. 2012), detecting the sources of urban air pollution (Xu et al. 2005), inferred soil organic carbon (Bae and Ryu 2015), evapotranspiration and plant water requirements (Nouri et al. 2016), and simulation of urban soil water content (Chiesi et al. 2019). *Synthetic aperture radar* (SAR) is an additional airborne or satellite-based sensing technique that effectively simulates a very large radar antenna ('aperture') by virtue of the different positions along the flight path, allowing high-resolution images and measurement of the height of objects or land elevations. SAR has been used for some years to map urban expansion and urban land use (e.g. Henderson and Xia 1997). Additional applications include estimation of soil water content (Moeremans and Dautrebande 2000), assessment of land subsidence (Tosi et al. 2009), building height (Colin-Koeniguer and Trouvé 2014), vegetation indices (Kim et al. 2014), impervious surface cover (Zhang et al. 2018), and flood water monitoring (Chini et al. 2019).

*Airborne data.* Aerial photography was probably the first remote sensing data layer to be used and is still commonly used in the mapping of urban land use or land surface cover (e.g. Grant and Finlayson 1978; Fox et al. 2012). High-resolution aerial photography has also been used as calibration data for analysis of satellite images (Ormsby 1982). Airborne radiometric data have been used widely in mineral exploration for several decades and have also provided information useful to urban areas. Relying on the natural radioactivity caused by low but detectable concentrations of radioactive potassium, thorium, and uranium isotopes, airborne radiometric measurements provide remotely sensed information to allow discrimination of solid earth-surface materials such as different types of rocks and soils. Airborne radiometric measurements have been used in an urban context by Beamish and Busby (2016) to assess peri-urban geological structures for geothermal potential. Another potentially fruitful application was described by Bierwirth and Brodie (2005), who found that the radiometric thorium (Th) signal was depleted in acid sulphate soil environments. Although Bierwirth and Brodie's (2005) study was not in an urban environment, the incidence of acid sulphate soil processes in new urban developments (especially in coastal areas) could make airborne radiometrics a useful monitoring tool.

## 5.5 Additional Reading

- Hillel D (2014) *Environmental soil physics: fundamentals, applications, and environmental considerations*. Academic Press, San Diego, USA
- Verma SK, Sharma SP (Eds.) (2011) *Urban Geophysics* (Special Issue with 21 articles). *Physics and Chemistry of the Earth, Parts A/B/C*, Vol. 36, Issue 16, pp. 1209–1436. Elsevier, Amsterdam, The Netherlands

## 5.6 Summary

Urban soils can have numerous physical constraints which affect their ability either to perform ecosystem services or to support urban infrastructure

The potentially adverse physical properties include:

- Surface or subsurface sealing
- High density and associated low porosity
- The existence of substantial proportions of coarse materials, artefacts, or buried infrastructure
- Weak or non-existent soil structure (for ecosystem services)
- Soil strength which is inappropriate to the desired soil functions
- High soil erodibility
- High soil temperatures

Adverse soil physical properties in urban environments may have undesirable effects on the ecosystem services or engineering functions of soils. The undesired effects may differ or even oppose one another depending on the soil management objectives (e.g. supporting vegetation or use as a structural foundation)

The physical properties of soils can be either static or dynamic. There are many methods for determining these properties, based on combinations of field and/or laboratory measurements. Some measurements must be made in situ in the field (e.g. infiltration rate or soil temperature), while others must be made in a laboratory (e.g. shear strength, particle density).

Soil physical morphology and properties are amenable to geophysical and remote sensing techniques to a greater degree than are soil biological or chemical measurements. Geophysical methods such as ground-penetrating radar, magnetic methods, or techniques based on electrical properties can provide useful information over larger spatial extents in urban soils. In addition remotely sensed (airborne or satellite) data has been used to estimate urban soil physical conditions.

## 5.7 Questions

### 5.7.1 *Checking Your Understanding*

1. Which soil physical constraints are likely to affect soil water storage and movement in urban soils? What is the nature of the effects that you have identified?
2. Some urban soil physical constraints are likely to affect soil biological functioning – what are these constraints? Which soil organisms might be affected and why?

3. Identify the soil physical processes which (a) have adverse effects on both ecosystem services and engineered structures and (b) have opposite effects on ecosystem services and engineered structures. Try to explain the differences!
4. Draw an annotated diagram which shows the water and heat fluxes (and any changes in these fluxes) involved in cooling of urban atmosphere and land surfaces by trees.
5. List the soil physical methods which directly or indirectly relate to measurement of soil water storage or movement. Describe which aspect of the behaviour of water in soils is being measured in each case.
6. Using examples, describe the differences between ground-based and remote sensing geophysical techniques for measurement or estimation of physical properties of urban soils.

(For the following sets of questions, you might need to do some additional reading.)

### 5.7.2 *Thinking About the Issues*

7. Explain why the analogy of a karst landscape is helpful for understanding water and solute flow in urban soils (or why it is not!).
8. Discuss the possible advantages and disadvantages of field versus laboratory measurement of the following soil physical properties: bulk density, water content, texture, penetration resistance, and electrical conductivity.
9. Is the often-cited water balance graphic (e.g. Fig. 5.1) still valid for urban ecosystems? Why (or why not)?

### 5.7.3 *Contemplating Soils Creatively*

10. Discuss whether it would be possible to remove the urban heat island effect in part or all of an urban area. What would be the best strategies for cooling soils in an urban environment?

## References

- Alexandrovskaia EI, Alexandrovskiy AL (2000) History of the cultural layer in Moscow and accumulation of anthropogenic substances in it. *Catena* 41:249–259. [https://doi.org/10.1016/S0341-8162\(00\)00107-7](https://doi.org/10.1016/S0341-8162(00)00107-7)
- Almeida MSS, Borma LS, Barbosa MC (2001) Land disposal of river and lagoon dredged sediments. *Eng Geol* 60:21–30. [https://doi.org/10.1016/S0013-7952\(00\)00085-5](https://doi.org/10.1016/S0013-7952(00)00085-5)
- Athanasopoulou E, Tombrou M, Russell AG, Karanasiou A, Eleftheriadis K, Dandou A (2010) Implementation of road and soil dust emission parameterizations in the aerosol model CAMx: Applications over the greater Athens urban area affected by natural sources. *J Geophys Res Atmos*:115. <https://doi.org/10.1029/2009JD013207>



- Bae J, Ryu Y (2015) Land use and land cover changes explain spatial and temporal variations of the soil organic carbon stocks in a constructed urban park. *Landsc Urban Plan* 136:57–67. <https://doi.org/10.1016/j.landurbplan.2014.11.015>
- Banks D, Gandy CJ, Younger PL, Withers J, Underwood C (2009) Anthropogenic thermogeological ‘anomaly’ in Gateshead, Tyne and Wear, UK. *Q J Eng Geol Hydrogeol* 42:307–312. <https://doi.org/10.1144/1470-9236/08-024>
- Beamish D, Busby J (2016) The Cornubian geothermal province: heat production and flow in SW England: estimates from boreholes and airborne gamma-ray measurements. *Geothermal Energy* 4. <https://doi.org/10.1186/s40517-016-0046-8>
- Bell RM, Failey RA (1991) Plant uptake of organic pollutants. In: Jones KC (ed) *Organic contaminants in the environment: environmental pathways & effects*, Elsevier Applied Science, pp 189–206. [https://doi.org/10.1007/978-94-009-4329-2\\_6](https://doi.org/10.1007/978-94-009-4329-2_6)
- Bierwirth PN, Brodie RS (2005) Identifying acid sulfate soil hotspots from airborne gamma-radiometric data and GIS analysis. Australian Government Bureau of Rural Sciences, Canberra
- Bonneau J, Fletcher TD, Costelloe JF, Burns MJ (2017) Stormwater infiltration and the ‘urban karst’ – a review. *J Hydrol* 552:141–150. <https://doi.org/10.1016/j.jhydrol.2017.06.043>
- Boschi F (2012) Magnetic prospecting for the archaeology of Classe (Ravenna). *Archaeol Prospect* 19:219–227. <https://doi.org/10.1002/arp.1430>
- Boudreault J-P, Dubé J-S, Chouteau M, Winiarski T, Hardy É (2010) Geophysical characterization of contaminated urban fills. *Eng Geol* 116:196–206. <https://doi.org/10.1016/j.enggeo.2010.09.002>
- British Standards Institution (1986) BS 8004: code of practice for foundations. UK, London
- Cardarelli E, Di Filippo G (2004) Integrated geophysical surveys on waste dumps: evaluation of physical parameters to characterize an urban waste dump (four case studies in Italy). *Waste Manag Res* 22:390–402. <https://doi.org/10.1177/0734242X040406042>
- Chan YC, Cohen DD, Hawas O, Stelcer E, Simpson R, Denison L et al (2008) Apportionment of sources of fine and coarse particles in four major Australian cities by positive matrix factorisation. *Atmos Environ* 42:374–389. <https://doi.org/10.1016/j.atmosenv.2007.09.030>
- Changnon SA (1999) A rare long record of deep soil temperatures defines temporal temperature changes and an urban heat island. *Clim Change* 42:531–538. <https://doi.org/10.1023/A:1005453217967>
- Chatterjea K (2007) Assessment and demarcation of trail degradation in a nature reserve, using GIS: case of Bukit Timah nature reserve. *Land Degrad Dev* 18:500–518. <https://doi.org/10.1002/ldr.793>
- Chen L, Zhu W, Zhou X, Zhou Z (2003) Characteristics of the heat island effect in Shanghai and its possible mechanism. *Adv Atmos Sci* 20:991–1001
- Chen Y, Day SD, Wick AF, McGuire KJ (2014) Influence of urban land development and subsequent soil rehabilitation on soil aggregates, carbon, and hydraulic conductivity. *Sci Total Environ* 494–495:329–336. <https://doi.org/10.1016/j.scitotenv.2014.06.099>
- Chiesi M, Battista P, Fibbi L, Gardin L, Pieri M, Rapi B et al (2019) Spatio-temporal fusion of NDVI data for simulating soil water content in heterogeneous Mediterranean areas. *Europ J Remote Sensing* 52:88–95. <https://doi.org/10.1080/22797254.2018.1557501>
- Chini M, Pelich R, Pulvirenti L, Pierdicca N, Hostache R, Matgen P (2019) Sentinel-1 InSAR coherence to detect floodwater in urban areas: Houston and hurricane Harvey as a test case. *Remote Sens (Basel)* 11. <https://doi.org/10.3390/rs11020107>
- Colin-Koeniguer E, Trouvé N (2014) Performance of building height estimation using high-resolution PolInSAR images. *IEEE Trans Geosci Remote Sens* 52:5870–5879. <https://doi.org/10.1109/TGRS.2013.2293605>
- Coutts AM, Tapper NJ, Beringer J, Loughnan M, Demuzere M (2013) Watering our cities: the capacity for water sensitive Urban Design to support urban cooling and improve human thermal comfort in the Australian context. *Prog Phys Geograph: Earth & Environ* 37:2–28. <https://doi.org/10.1177/0309133312461032>

- Cresswell H, Coughlan K, McKenzie N (2002) Soil physical measurement and interpretation for land evaluation. CSIRO Publishing, Victoria, Australia, ix, 379 pp.
- Dane JH, Clarke Topp G (Eds.) (2002) Methods of soil analysis. Part 4. Physical methods. SSSA Book Series, Number 5. Soil Science Society of America, Inc., Madison, Wisconsin, USA
- de Lima RP, da Silva AR, da Silva AP, Leao TP, Mosaddeghi MR (2016) Soilphysics: an R package for calculating soil water availability to plants by different soil physical indices. *Comput Electron Agric* 120:63–71. <https://doi.org/10.1016/j.compag.2015.11.003>
- Del Mar López T, Aide TM, Scatena FN (1998) The effect of land use on soil erosion in the Guadiana watershed in Puerto Rico. *Caribb J Sci* 34:298–307
- Department of Environment (2004) Chapter 7 Non-structural controls. Stormwater Management Manual for Western Australia, Chalmers, L., Gray, S. (Eds.). Government of Western Australia, Perth, Australia
- El Khalil H, Schwartz C, El Hamiani O, Sirguey C, Kubiniok J, Boularbah A (2016) How physical alteration of technic materials affects mobility and phytoavailability of metals in urban soils? *Chemosphere* 152:407–414. <https://doi.org/10.1016/j.chemosphere.2016.02.116>
- Eliasson I, Jonsson P, Holmer B (2008) Diurnal and intra-urban particle concentrations in relation to windspeed and stability during the dry season in three African cities. *Environ Monit Assess* 154:309. <https://doi.org/10.1007/s10661-008-0399-y>
- Erskine WD, Mahmoudzadeh A, Browning CM, Myers C (2003) Sediment yields and soil loss rates from different land uses on Triassic shales in western Sydney, NSW. *Soil Res* 41:127–140. <https://doi.org/10.1071/SR01078>
- Fletcher T, Duncan H, Poelsma P, Lloyd S (2004) Stormwater flow and quality, and the effectiveness of non-proprietary Stormwater treatment measures : a review and gap analysis. Technical Report 04/8, Melbourne, Australia
- Foster GR, Toy TE, Renard KG (2003) Comparison of the USLE, RUSLE1.06c, and RUSLE2 for application to highly disturbed lands, Proc. Interagency Conf. on Research in the Watersheds, 1st, Benson, AZ, USA, pp. 154–160
- Fourvel GJ, Vidal-Beaudet L, Le Bocq A, They F, Brochier V, Cannavo P (2019) Fertility of Technosols constructed with dam sediments for urban greening and land reclamation. *J Soil Sediment* 19:3178–3192. <https://doi.org/10.1007/s11368-018-2077-1>
- Fox DM, Witz E, Blanc V, Soulié C, Penalver-Navarro M, Dervieux A (2012) A case study of land cover change (1950-2003) and runoff in a Mediterranean catchment. *Appl Geogr* 32:810–821. <https://doi.org/10.1016/j.apgeog.2011.07.007>
- Geotechdata.info (2015) Soil bearing capacity, <http://geotechdata.info/parameter/bearing-capacity.html> (accessed 20190808)
- Gleason FH, Letcher PM, McGee PA (2004) Some Chytridiomycota in soil recover from drying and high temperatures. *Mycol Res* 108:583–589. <https://doi.org/10.1017/S0953756204009736>
- Grant K, Finlayson AA (1978) The assessment and evaluation of geotechnical resources in urban or regional environments. *Eng Geol* 12:219–293. [https://doi.org/10.1016/0013-7952\(78\)90014-5](https://doi.org/10.1016/0013-7952(78)90014-5)
- Grimm NB, Faeth SH, Golubiewski NE, Redman CL, Wu J, Bai X, Briggs JM (2008) Global change and the ecology of cities. *Science* 319:756–760
- Gwenzi W, Nyamadzawo G (2014) Hydrological impacts of urbanization and urban roof water harvesting in water-limited catchments: a review. *Environ Process* 1:573–593. <https://doi.org/10.1007/s40710-014-0037-3>
- Hafner J, Kidder SQ (1999) Urban heat island modeling in conjunction with satellite-derived surface/soil parameters. *J Appl Meteorol* 38:448–465. [https://doi.org/10.1175/1520-0450\(1999\)038<0448:UHIMIC>2.0.CO;2](https://doi.org/10.1175/1520-0450(1999)038<0448:UHIMIC>2.0.CO;2)
- Hancox GT (2008) The 1979 Abbotsford landslide, Dunedin, New Zealand: a retrospective look at its nature and causes. *Landslides* 5:177–188. <https://doi.org/10.1007/s10346-007-0097-9>
- Hazelton P, Murphy B (2011) Understanding Soils in Urban Environments. CSIRO Publishing, Collingwood, Australia, 160 pp

- Henderson FM, Xia ZG (1997) SAR applications in human settlement detection, population estimation and urban land use pattern analysis: a status report. *IEEE Trans Geosci Remote Sens* 35:79–85. <https://doi.org/10.1109/36.551936>
- Hillel D (2014) *Environmental soil physics fundamentals, applications, and environmental considerations*. Academic Press, San Diego
- Hulisz P, Charzyński P, Greinert A (2018) Urban soil resources of medium-sized cities in Poland: a comparative case study of Toruń and Zielona Góra. *J Soil Sediment* 18:358–372. <https://doi.org/10.1007/s11368-016-1596-x>
- Jim CY (1998a) Soil characteristics and management in an urban park in Hong Kong. *Environ Manag* 22:683–695. <https://doi.org/10.1007/s002679900139>
- Jim CY (1998b) Urban soil characteristics and limitations for landscape planting in Hong Kong. *Landsc Urban Plan* 40:235–249. [https://doi.org/10.1016/S0169-2046\(97\)00117-5](https://doi.org/10.1016/S0169-2046(97)00117-5)
- Julian M, Anthony E (1996) Aspects of landslide activity in the Mercantour Massif and the French Riviera, southeastern France. *Geomorphology* 15:275–289. [https://doi.org/10.1016/0169-555X\(95\)00075-G](https://doi.org/10.1016/0169-555X(95)00075-G)
- Khresat SA, Rawajfih Z, Mohammad M (1998) Land degradation in North-Western Jordan: causes and processes. *J Arid Environ* 39:623–629. <https://doi.org/10.1006/jare.1998.0385>
- Kim YH, Oh JH, Kim YI (2014) Comparative analysis of the multispectral vegetation indices and the radar vegetation index. *J Korean Soc Surv Geod Photogramm Cartogr* 32:607–615. <https://doi.org/10.7848/ksgpc.2014.32.6.607>
- Knox EG, Bouchard CE, Barrett JG (2000) Erosion and sedimentation in urban areas (chapter 7). In: Brown RB, Huddleston JH, Anderson JL (eds) *Managing soils in an urban environment*. Agronomy Monograph. American Society of Agronomy, Crop Science Society of America, Soil Science Society of America, Madison, WI, pp 179–197. <https://doi.org/10.2134/agron-monogr39.c7>
- Kumar K, Hundal L (2016) Soil in the city: sustainably improving urban soils. *J Environ Qual* 45:2–8. <https://doi.org/10.2134/jeq2015.11.0589>
- Lafflen JM, Flanagan DC (2013) The development of U. S. soil erosion prediction and modeling. *Int Soil & Water Conserv Res* 1:1–11. [https://doi.org/10.1016/S2095-6339\(15\)30034-4](https://doi.org/10.1016/S2095-6339(15)30034-4)
- Landsberg HE, Maisel TN (1972) Micrometeorological observations in an area of urban growth. *Bound-Lay Meteorol* 2:365–370. <https://doi.org/10.1007/bf02184776>
- Leopold M, Gannaway E, Volkel J, Haas F, Becht M, Heckmann T et al (2011) Geophysical prospection of a bronze foundry on the southern slope of the acropolis at Athens, Greece. *Archaeol Prospect* 18:27–41. <https://doi.org/10.1002/arp.402>
- Li X, Chang SX, Salifu KF (2013) Soil texture and layering effects on water and salt dynamics in the presence of a water table: a review. *Environ Rev* 22:41–50. <https://doi.org/10.1139/er-2013-0035>
- Lin BS, Lin YJ (2010) Cooling effect of shade trees with different characteristics in a subtropical urban park. *HortScience* 45:83–86
- Liu C, Evett JB (2008) *Soils and foundations*, 7th edn. Pearson/Prentice Hall, Upper Saddle River, NJ
- Lubczynski M, Roy J (2003) Hydrogeological interpretation and potential of the new magnetic resonance sounding (MRS) method. *J Hydrol* 283:19–40. [https://doi.org/10.1016/S0022-1694\(03\)00170-7](https://doi.org/10.1016/S0022-1694(03)00170-7)
- Magiera T, Strzyszcz Z, Kapicka A, Petrovsky E (2006) Discrimination of lithogenic and anthropogenic influences on topsoil magnetic susceptibility in Central Europe. *Geoderma* 130:299–311. <https://doi.org/10.1016/j.geoderma.2005.02.002>
- Mao Q, Huang G, Buyantuev A, Wu J, Luo S, Ma K (2014) Spatial heterogeneity of urban soils: the case of the Beijing metropolitan region, China. *Ecological Process* 3. <https://doi.org/10.1186/s13717-014-0023-8>
- Martin A, Gunter JT, Regens JL (2003) Estimating erosion in a riverine watershed: Bayou Liberty-Tchefuncta river in Louisiana. *Environ Sci Pollut Res* 10:245–250. <https://doi.org/10.1065/espr2003.05.153>

- McKenzie NJ, Jacquier D, Isbell R, Brown K (2004) Australian soils and landscapes: an illustrated compendium. CSIRO Publishing, Collingwood, VIC
- McLean MA, Angilletta MJ Jr, Williams KS (2005) If you can't stand the heat, stay out of the city: thermal reaction norms of chitinolytic fungi in an urban heat island. *J Therm Biol* 30:384–391. <https://doi.org/10.1016/j.jtherbio.2005.03.002>
- Metwaly M, El-Qady G, Massoud U, El-Kenawy A, Matsushima J, Al-Arifi N (2010) Integrated geoelectrical survey for groundwater and shallow subsurface evaluation: case study at Siliyin spring, El-Fayoum, Egypt. *Int J Earth Sci* 99:1427–1436. <https://doi.org/10.1007/s00531-009-0458-9>
- Min M, Lin C, Duan X, Jin Z, Zhang L (2019) Spatial distribution and driving force analysis of urban heat island effect based on raster data: a case study of the Nanjing metropolitan area, China. *Sustain Cities Soc* 50:101637. <https://doi.org/10.1016/j.scs.2019.101637>
- Moeremans B, Dautrebande S (2000) Soil moisture evaluation by means of multi-temporal ERS SAR PRI images and interferometric coherence. *J Hydrol* 234:162–169. [https://doi.org/10.1016/S0022-1694\(00\)00251-1](https://doi.org/10.1016/S0022-1694(00)00251-1)
- Montague T, Kjelgren R (2004) Energy balance of six common landscape surfaces and the influence of surface properties on gas exchange of four containerized tree species. *Sci Hortic* 100:229–249. <https://doi.org/10.1016/j.scienta.2003.08.010>
- Morel JL, Chenu C, Lorenz K (2015) Ecosystem services provided by soils of urban, industrial, traffic, mining, and military areas (SUITMAs). *J Soil Sediment* 15:1659–1666. <https://doi.org/10.1007/s11368-014-0926-0>
- Morgenroth J, Buchan GD (2009) Soil moisture and aeration beneath pervious and impervious pavements. *Arboriculture and Urban Forestry* 35:135–141
- Morin TH, Bohrer G, Frasson RPD, Naor-Azreli L, Mesi S, Stefanik KC, Schäfer KVR (2014) Environmental drivers of methane fluxes from an urban temperate wetland park. *J Geophys Res G: Biogeosci* 119:2188–2208. <https://doi.org/10.1002/2014JG002750>
- Nouri H, Glenn EP, Beecham S, Boroujeni SC, Sutton P, Alaghmand S et al (2016) Comparing three approaches of evapotranspiration estimation in mixed urban vegetation: field-based, remote sensing-based and observational-based methods. *Remote Sens (Basel)* 8. <https://doi.org/10.3390/rs8060492>
- Nunziata C, Natale M, Panza GF (2004) Seismic characterization of Neapolitan soils. *Pure Appl Geophys* 161:1285–1300. <https://doi.org/10.1007/s00024-003-2492-z>
- Ormsby JP (1982) The use of Landsat-3 thermal data to help differentiate land covers. *Remote Sens Environ* 12:97–105. [https://doi.org/10.1016/0034-4257\(82\)90029-3](https://doi.org/10.1016/0034-4257(82)90029-3)
- Ozsoy G, Aksoy E (2015) Estimation of soil erosion risk within an important agricultural sub-watershed in Bursa, Turkey, in relation to rapid urbanization. *Environ Monit Assess* 187:419. <https://doi.org/10.1007/s10661-015-4653-9>
- Paul MJ, Meyer JL (2001) Streams in the urban landscape. *Annu Rev Ecol Syst* 32:333–365
- Pavao-Zuckerman MA, Coleman DC (2005) Decomposition of chestnut oak (*Quercus prinus*) leaves and nitrogen mineralization in an urban environment. *Biol Fertil Soils* 41:343–349. <https://doi.org/10.1007/s00374-005-0841-z>
- Peters EB, McFadden JP (2010) Influence of seasonality and vegetation type on suburban micro-climates. *Urban Ecosyst* 13:443–460. <https://doi.org/10.1007/s11252-010-0128-5>
- Phinn S, Stanford M, Scarth P, Murray AT, Shyy PT (2002) Monitoring the composition of urban environments based on the vegetation-impervious surface-soil (VIS) model by subpixel analysis techniques. *Int J Remote Sens* 23:4131–4153. <https://doi.org/10.1080/01431160110114998>
- Rahardjo H, Indrawan IGB, Leong EC, Yong WK (2008) Effects of coarse-grained material on hydraulic properties and shear strength of top soil. *Eng Geol* 101:165–173. <https://doi.org/10.1016/j.enggeo.2008.05.001>
- Rashed M, Atef A (2015) Mapping underground utilities within conductive soil using multi-frequency electromagnetic induction and ground penetrating radar. *Arab J Geosci* 8:2341–2346. <https://doi.org/10.1007/s12517-014-1358-2>

- Renard KG, Foster GR, Weesies GA, McCool DK, Yoder DC (1997) Predicting soil erosion by water: a guide to conservation planning with the revised universal soil loss equation (RUSLE). Agriculture handbook no. 703, U.S. Department of Agriculture, Washington DC, USA. [https://www.ars.usda.gov/ARUserFiles/64080530/RUSLE/AH\\_703.pdf](https://www.ars.usda.gov/ARUserFiles/64080530/RUSLE/AH_703.pdf)
- Rocha JHT, Santos AJM, Diogo FA, Backes C, De Melo AGC, Borelli K, De Oliveira Godinho T (2015) Reforestation and recovery of soil chemical and physical attributes [in Portuguese]. *Floresta e Ambiente* 22:299–306. <https://doi.org/10.1590/2179-8087.041613>
- Rowlands L (2018) Erosion and sediment control - WSUD during the construction phase of land development. In: Sharma AK, Gardner T, Begbie D (eds) Approaches to water sensitive urban design. Elsevier Science & Technology, Amsterdam, pp 163–176
- Saarenketo T, Scullion T (2000) Road evaluation with ground penetrating radar. 43: 119–138. [https://doi.org/10.1016/S0926-9851\(99\)00052-X](https://doi.org/10.1016/S0926-9851(99)00052-X)
- Savva Y, Szlavecz K, Pouyat RV, Groffman PM, Heisler G (2010) Effects of land use and vegetation cover on soil temperature in an urban ecosystem. *Soil Sci Soc Am J* 74:469–480. <https://doi.org/10.2136/sssaj2009.0107>
- Scharenbroch BC, Lloyd JE, Johnson-Maynard JL (2005) Distinguishing urban soils with physical, chemical, and biological properties. *Pedobiologia* 49:283–296. <https://doi.org/10.1016/j.pedobi.2004.12.002>
- Schneider A, Logan KE, Kucharik CJ (2012) Impacts of urbanization on ecosystem goods and services in the U.S. corn belt. *Ecosystems* 15:519–541. <https://doi.org/10.1007/s10021-012-9519-1>
- Short JR, Fanning DS, Foss JE, Patterson JC (1986a) Soils of the Mall in Washington, DC: II. Genesis, classification, and mapping. *Soil Sci Soc Am J* 50:705–710. <https://doi.org/10.2136/sssaj1986.03615995005000030031x>
- Short JR, Fanning DS, McIntosh MS, Foss JE, Patterson JC (1986b) Soils of the Mall in Washington, DC: I. statistical summary of Properties I. *Soil Sci Soc Am J* 50:699–705. <https://doi.org/10.2136/sssaj1986.03615995005000030030x>
- Small C (2006) Comparative analysis of urban reflectance and surface temperature. *Remote Sens Environ* 104:168–189. <https://doi.org/10.1016/j.rse.2005.10.029>
- Stokes A, Fourcaud T, Hruska J, Cermak J, Nadyezhdina N, Nadyezhdin V, Praus L (2002) An evaluation of different methods to investigate root system architecture of urban trees in situ: I. ground-penetrating radar. *J Arboric* 28:2–10
- Sutherland RA (2000) Bed sediment-associated trace metals in an urban stream, Oahu, Hawaii. *Environ Geol* 39:611–627
- Tang CS, Shi B, Gao L, Daniels JL, Jiang HT, Liu C (2011) Urbanization effect on soil temperature in Nanjing, China. *Energ Buildings* 43:3090–3098. <https://doi.org/10.1016/j.enbuild.2011.08.003>
- Terzaghi K, Peck RB, Mesri G (1996) Soil mechanics in engineering practice, third edition. Wiley, New York, 549 pp, doi:0471086584
- Tosi L, Teatini P, Carbognin L, Brancolini G (2009) Using high resolution data to reveal depth-dependent mechanisms that drive land subsidence: the Venice coast, Italy. *Tectonophysics* 474:271–284. <https://doi.org/10.1016/j.tecto.2009.02.026>
- U.S. EPA (2011) Evaluation of urban soils: suitability for green infrastructure or urban agriculture, United States Environmental Protection Agency, Washington, DC, USA. <https://ucanr.edu/sites/UrbanAg/files/263151.pdf>
- USDA (2000) Erosion and sedimentation on construction sites, urban technical note. No. 1, United States Department of Agriculture, Natural Resources Conservation Service, Auburn, AL, USA
- USEPA (1993) Guidance specifying management measures for sources of nonpoint source pollution in coastal waters. 840-B-92-002, United States Environmental Protection Agency, Washington DC, USA. <https://www.epa.gov/nps/guidance-specifying-management-measures-sources-nonpoint-pollution-coastal-waters>
- USGA (2018) USGA recommendations for a method of putting green construction, 2018 revision. United States Golf Association, Liberty Corner

- Uzielli M, Lacasse S, Nadim F, Phoon K-K (2006) Soil variability analysis for geotechnical practice. Proceedings of the 2nd International Workshop on Characterisation and Engineering Properties of Natural Soils. Taylor & Francis, Singapore, pp. 103. <https://doi.org/10.1201/NOE0415426916.ch3>
- Volder A, Watson T, Viswanathan B (2009) Potential use of pervious concrete for maintaining existing mature trees during and after urban development. *Urban Forest & Urban Green* 8:249–256. <https://doi.org/10.1016/j.ufug.2009.08.006>
- Wang H, Ouyang Z, Chen W, Wang X, Zheng H, Ren Y (2011) Water, heat, and airborne pollutants effects on transpiration of urban trees. *Environ Pollut* 159:2127–2137. <https://doi.org/10.1016/j.envpol.2011.02.031>
- Weissert LF, Salmond JA, Schwendenmann L (2016) Variability of soil organic carbon stocks and soil CO<sub>2</sub> efflux across urban land use and soil cover types. *Geoderma* 271:80–90. <https://doi.org/10.1016/j.geoderma.2016.02.014>
- White RE (2006) Principles and practice of soil science: the soil as a natural resource. Blackwell Science Ltd., Malden, MA
- Wolman MG, Schick AP (1967) Effects of construction on fluvial sediment, urban and suburban areas of Maryland. *Water Resour Res* 3:451–464. <https://doi.org/10.1029/WR003i002p00451>
- Wong CI, Sharp JM Jr, Hauwert N, Landrum J, White KM (2012) Impact of urban development on physical and chemical hydrogeology. *Elements* 8:429–434. <https://doi.org/10.2113/gselements.8.6.429>
- Wu C, Murray AT (2003) Estimating impervious surface distribution by spectral mixture analysis. *Remote Sens Environ* 84:493–505. [https://doi.org/10.1016/s0034-4257\(02\)00136-0](https://doi.org/10.1016/s0034-4257(02)00136-0)
- Xiao RB, Ouyang ZY, Li WF, Zhang ZM, Tarver G Jr, Wang XK, Miao H (2005) A review of the eco-environmental consequences of urban heat islands. *Acta Ecol Sin* 25:2055–2060
- Xu X, Zhou X, Shi X (2005) Spatial structure and scale feature of the atmospheric pollution source impact of city agglomeration. *Sci China Ser D Earth Sci* 48:1–24. <https://doi.org/10.1360/03YD0125>
- Zhang H, Lin H, Wang Y (2018) A new scheme for urban impervious surface classification from SAR images. *ISPRS J Photogramm Remote Sens* 139:103–118. <https://doi.org/10.1016/j.isprsjprs.2018.03.007>
- Zhu WX, Carreiro MM (2004) Variations of soluble organic nitrogen and microbial nitrogen in deciduous forest soils along an urban-rural gradient. *Soil Biol Biochem* 36:279–288. <https://doi.org/10.1016/j.soilbio.2003.09.011>
- Ziska LH, Bunce JA, Goins EW (2004) Characterization of an urban-rural CO<sub>2</sub>/temperature gradient and associated changes in initial plant productivity during secondary succession. *Oecologia* 139:454–458. <https://doi.org/10.1007/s00442-004-1526-2>
- Zou C, Penfold C, Sands R, Misra RK, Hudson I (2001) Effects of soil air-filled porosity, soil matric potential and soil strength on primary root growth of radiata pine seedlings. *Plant and Soil* 236:105–115. <https://doi.org/10.1023/A:1011994615014>