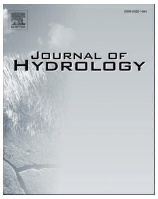
Journal of Hydrology 557 (2018) 631–642

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol



Review papers

Does soil compaction increase floods? A review

Abdallah Alaoui [a,*], Magdalena Rogger [b], Stephan Peth [c], Günter Blöschl [b]

[a] *University of Bern, Bern, Switzerland*
[b] *Institute of Hydraulic Engineering and Water Resources Management, Vienna University of Technology, Vienna, Austria*
[c] *Department of Soil Science, University of Kassel, Kassel, Germany*

ARTICLE INFO

Article history:
Received 8 August 2017
Received in revised form 19 December 2017
Accepted 20 December 2017
Available online 26 December 2017
This manuscript was handled by Marco Borga, Editor-in-Chief, with the assistance of Daniele Penna, Associate Editor

Keywords:
Soil compaction
Floods
Land use changes
Soil hydrology
Upscaling flow processes

ABSTRACT

Europe has experienced a series of major floods in the past years which suggests that flood magnitudes may have increased. Land degradation due to soil compaction from crop farming or grazing intensification is one of the potential drivers of this increase. A literature review suggests that most of the experimental evidence was generated at plot and hillslope scales. At larger scales, most studies are based on models. There are three ways in which soil compaction affects floods at the catchment scale: (i) through an increase in the area affected by soil compaction; (ii) by exacerbating the effects of changes in rainfall, especially for highly degraded soils; and (iii) when soil compaction coincides with soils characterized by a fine texture and a low infiltration capacity. We suggest that future research should focus on better synthesising past research on soil compaction and runoff, tailored field experiments to obtain a mechanistic understanding of the coupled mechanical and hydraulic processes, new mapping methods of soil compaction that combine mechanical and remote sensing approaches, and an effort to bridge all disciplines relevant to soil compaction effects on floods.

Contents

---

[*] Corresponding author.
E-mail address: abdallah.alaoui@cde.unibe.ch (A. Alaoui).

https://doi.org/10.1016/j.jhydrol.2017.12.052
0022-1694/

---

1. Introduction

Europe has experienced a series of major floods in the past years which may suggest that flooding is becoming more frequent and severe (e.g., Hall et al., 2014). Destructive floods occurred in several European countries like Germany and Poland in August 2002, in western Austria in 2005, in Italy in November 1994, October 2000, and autumn 2011; the UK in October 2000, summer 2007, and the winters of 2013/14 and 2015/16; in Central Europe in July 1997, summer 2010, and June 2013; the Balkan region in May 2014; and, most recently, in Germany, France and Belgium in June 2016 (Kundzewicz et al., 2017). In order to project any changes into the future it is important to understand the drivers that have triggered flood changes in the past. There are three potential drivers, climate change, hydraulic structures and land use change (Viglione et al., 2016; Hall et al., 2014; Blöschl et al., 2017). Among these, land use change effects are probably the least well understood (e.g., Peña et al., 2016; Rogger et al., 2017).

Humans have interfered with landscapes over millennia, at an ever increasing rate. In the last centuries, global rain-fed cropland and pastureland have increased by 460% and 560%, respectively (Scanlon et al., 2007). Land use change tends to follow a set pattern: from the restoration of natural vegetation to boundary clearing, then to subsistence agriculture and small-scale farms and, as a final point, to intensive agriculture, urban areas and protected recreational lands (Foley et al., 2005). These land use changes are often associated with soil degradation, particularly if heavy machinery is used, but grazing intensification may also lead to major modifications of the soils (Carroll et al., 2004; O'Connell et al., 2004). Some 33 million hectares are affected by soil compaction in Europe (Oldeman et al., 1991, cited by Birkas, 2008). Of these, 20 million hectares are in Eastern Europe, which amounts to 37.5% of the agricultural land (Birkas, 2008; Batey, 2009).

Soil compaction can cause a number of environmental and agronomic problems, including increased leaching of agrochemicals to the recipient waters, emission of greenhouse gases, crop yield losses, erosion and flooding (Holman et al., 2003; Doerner and Horn, 2006; Singh and Hadda, 2014). While soil compaction effects on surface runoff are relatively well understood at the local scale (Rogger et al., 2017), the larger-scale effects are rather elusive and the literature is rather fragmented. To the best of the authors' knowledge, no literature review has been published on the impacts of soil compaction on flood processes at the catchment scale. The main aim of this review is to summarise current knowledge on the subject in an organised way, identify gaps and propose new avenues to better understanding soil compaction effects on floods. While the focus is on soil compaction effects on floods, we refer to land use instead of soil compaction in cases where the degree of compaction is not specifically quantified in the literature.

2. Soil compaction processes

2.1. Types and causes of soil compaction

Compaction is defined as an increase in soil bulk density and reduction in soil porosity (Boone, 1988; da Silva et al., 1994). In contrast, soil shearing does not necessarily reduce soil porosity, but does destroy the continuity of macropores (e.g., Horn et al., 1995; Alaoui et al., 2011a). Together they are referred to as soil deformation (e.g., Alaoui et al., 2011a).

The ability of a soil to resist non-recoverable deformation during loading (the soil strength) is influenced by several factors such as texture, structure, organic matter content and in particular the soil water content (Gill and Vanden Berg, 1967; Horn, 1988). The behaviour of a soil during loading is therefore usually examined as a function of soil water content (Young and Warkentin, 1966). Soil strength can be estimated from stress-strain relationships obtained from laboratory experiments (Casagrande, 1936) or from pedo-transfer functions (Van den Akker, 2004; Horn and Fleige, 2003). The vulnerability to compaction may be assessed by comparing soil strength with the vertical loading. Soil compaction may affect the surface and the subsurface.

Surface (topsoil) compaction: Compaction at the soil surface (down to the depth reached by tillage) may result from stock grazing (trampling) and traffic loading (Table 1). Trampling effects depend on stock density, animal weight, hoof size, soil moisture, soil type, plant type and field slope (e.g., Zhao et al., 2010; Krümmelbein et al., 2006). It mainly affects the pore geometry at the soil surface (Nie et al., 2001; Vzzotto et al., 2000) and the topsoil matrix (Alaoui and Helbling, 2006). It may reduce the number of earthworms, resulting in an additional reduction in infiltration (e.g., Hills, 1971). The compaction depth does not usually exceed 10 cm (Greenwood and McKenzie 2001). Surface compaction may result from traffic loading, especially from tractors with mounted or trailed implements. Below the contact surface between soil and tire, the soil deforms under normal and shear stresses (e.g. Horn and Rostek, 2000). The shear stress rises sharply with an increase in traction force and wheel slip, which may lead to the detachment of a weak topsoil layer vulnerable to erosion and surface runoff (Battiato et al., 2013). Tractor passes can form an anisotropic soil pore system due to the simultaneous movement of particles forward and downwards and to wheel slippage (Pagliai et al., 2003; Peng and Horn, 2008). The changes can form a platy structure in the upper few centimetres with elongated pores that are oriented parallel to the soil surface. These pores are not vertically continuous and induce mainly horizontal water fluxes (Horn et al., 2003; Pagliai et al., 2003).

Subsurface (subsoil) compaction: The mechanical strength of structured (characterized by the matrix and macropore domains) soils mainly depends on aggregation, actual and maximum predrying, and the composition and arrangement of the pore system

Table 1
Types and causes of soil compaction.

Type of compaction	Description/causes	Example references
Traffic loads	The principal causes of compaction are compressive forces applied to compressible soil from wheels under tractors, trailers and harvesters, during the passage of tillage implements on the soil (particularly powered rotary equipment)	Hamza and Anderson (2005), Arvidsson et al. (2002), Milne and Haynes (2004)
Cattle grazing/stock trampling	Trampling-induced soil compaction in a pasture characterized by its spatially heterogeneous distribution. It mainly affects pore geometry (or structure) at the soil surface (surface compaction)	Alaoui et al. (2011a), Krümmelbein et al. (2006), Vzzotto et al. (2000)
Puddling	Tillage induced compaction of the subsoil in paddy rice fields leading to hardpans during cultivation in water saturated conditions	Samson et al. (2002)
Urbanization	Caused by the use of heavy machinery, the relocation of building materials, and trampling by humans, especially near sidewalks or driveways, at construction sites, and in public green spaces	Edmonson et al. (2011), Jim (1998), Pouyat et al. (2007)
Industrial activities	Caused during extraction of minerals, installation of underground pipelines or remodelled landscapes using heavy machinery	Batey (2009), Batey and McKenzie (2006)

(Horn and Rostek, 2000). The more negative the pore water pressure, the more pronounced is the strength increase. Thus, under humid climatic conditions soils usually get weaker with depth. Subsoil compaction risks increase with farm size, machine weight (e.g., harvester) and the drive for greater productivity. Once subsoil damage occurs, it can be extremely difficult and expensive to alleviate (Jones et al., 2003). Usually, the first pass of a wheel causes a major portion of the total topsoil compaction (Bakker and Davis, 1995; Botta et al., 2006; Silva et al., 2008), whereas repeated traffic with low axle loads can affect the subsoil (Balbuena et al., 2000; Hamza and Anderson, 2005).

2.2. Soil properties

2.2.1. Soil structure

Laboratory experiments have shown that the inter-aggregate structure of soils is more susceptible to compaction than the soil aggregates themselves (Li and Zhang, 2009). Macroporosity is therefore more sensitive to compaction than total porosity (Alakukku, 1996). Jégou et al. (2002) showed that soil compaction decreases the continuity of burrow systems. Soils with mainly horizontal pores are more susceptible to compaction than those with vertical pores (Hartge and Bohne, 1983; Schäffer et al., 2008).

2.2.2. Soil texture

The degree of compaction (actual bulk density expressed as a percentage of the reference-compaction state of a given soil, Håkansson and Lipiec, 2000) also depends on soil texture. For example, silt loam soils with low colloid contents are more susceptible than medium or fine textured loamy and clayey soils at low water contents, while sandy soils are only slightly susceptible to soil compaction (Horn et al., 1995). Smith et al. (1997) showed that a loamy soil subjected to varied pressures and moisture contents was resistant to compaction when dried and susceptible to compaction when wet, while a loamy sand soil showed smaller increases in compaction with increasing load and moisture content.

2.2.3. Organic matter

Increases in soil organic matter may reduce compactibility by increasing resistance to deformation and/or by increasing elasticity (rebound effects; Soane, 1990). High organic carbon contents can even reduce soil compaction at high moisture levels in clay and silty clay soils (Smith et al.,1997; Nawaz et al., 2013; Hamza and Anderson, 2005; Smith et al., 1997).

2.2.4. Water content

Soil water content is usually the most important factor influencing soil compaction (Soane and Van Ouwerkerk, 1994; Hamza and Anderson, 2005). Traffic experiments on arable land with heavy excavators (weighing up to 47 tons) showed a decrease in the frequency and volume of macropores down to depths of 0.65 m and 1.0 m for dry and wet soils, respectively (Dumbeck, 1984). Wet conditions in autumn, winter and spring exacerbate the effect of heavy machinery on compaction. Arvidsson et al. (2001) showed that the risk of soil compaction with commonly used machinery in southern Sweden is 100% for spring slurry application and more than 60% after October in sugar beet harvesting. Yung et al. (2010) found that high compaction was due to the footslope staying wetter for a longer period during the spring and early summer because of cover crop residues.

2.3. Time scales of soil compaction

Environmental and management related factors tend to interact on different time scales in driving the temporal dynamics of the structure related soil hydraulic properties (Mapa et al., 1986; Kay, 1990; Bodner et al., 2013). For example, Kohl and Markart (2002) showed that compaction effects are usually largest in autumn after the grazing period, but soils may recover during winter and spring due to freezing/thawing processes, plant root activity and microbial activity. Soils which are wet during critical times of land management operations, such as ploughing and harvesting, can be prone to compaction and structural damage (Earl, 1997; Holman et al., 2003) and can result in long term effects that are mainly observed where a plough pan (a compacted layer that tends to form just below the ploughing depth) develops. A stable, natural soil structure may only be achieved after several years when changing practices from regular soil loosening to no-tillage (Wright et al., 1999). Soils under long term no-tillage with low "self-mulching potential" (low clay and organic matter content) may tend towards high bulk density and low water permeability (Munkholm et al., 2003).

Persistent compaction effects are often observed for the subsoil of agriculturally used fields. Even after their abandonment, soil compaction may be persistent over decades (Kellner and Hubbart, 2016), indicating a long memory effect. Potential factors controlling this memory are land-use, soil type, topography and climate (Cambi et al., 2015; Rogger et al., 2017). For some soils, the compaction may be measurable even after 14 years (Berisso et al., 2012; Etana et al., 2013), and may persist over 30 years if underground pipelines have been installed or the landscape remodelled using heavy machinery (Batey, 2009). The impact of 13 years of cattle grazing was still measurable in a secondary teak forest after 10 years of growth (Zimmermann et al., 2006), and former agricultural plots showed increased runoff 30 years after afforestation (Hümann et al., 2011). While some forest soils tend to recover in a few years (Mace, 1971; Shoulders and Terry, 1978), others take 10–20 years to recover from shallow compaction (Dickerson, 1976; Froehlich, 1979; Jakobsen, 1983). Compaction of deep layers can persist over 100 years (Greacen and Sands, 1980).

2.4. Macropore flow – surface runoff relationship

Macropores (i.e., biopores) represent only 0.23–2.00% of the total soil volume, but may account for about 74–100% of the total water flux (Alaoui and Helbling, 2006). They are the most sensitive pores to compaction. Their volume reduction may significantly reduce vertical infiltration and thus increase surface runoff (e.g., Gerke, 2006; Hendrickx and Flury, 2001; Alaoui, 2015). Severing their connectivity between the top-few centimetres and the underlying macropores additionally reduces infiltration (Alaoui et al., 2011b; Jégou et al., 2002; Alaoui, 2015).

The flow through macropores depends on the initial and boundary conditions and the exchange between the matrix and macropore domains which in turn depends on soil moisture, texture, degree of compaction and organic matter (Kluitenberg and Horton, 1990; Zehe and Blöschl, 2004; McGrath et al., 2009; Larsbo, 2011). Since these variables are rarely known at the field scale (Jarvis et al., 2012), one usually resorts to quantifying their spatially integrated effects as effective hydraulic properties (Blöschl and Sivapalan, 1995). One possibility is to classify these properties into pedons or spatial units (Addiscott and Mirza, 1998; Seyfried and Wilcox, 1995). An interesting observation is that of structural hierarchy (Brewer, 1964; Hadas, 1987; Dexter, 1988; Dexter et al., 2008). The mean sizes of the pores separating the soil aggregates at progressively higher levels are themselves progressively bigger (e.g., Dexter et al., 2008). This structural hierarchy can be extended to the hillslope scale. In humid climates, lateral preferential flow can dominate stream response in catchments with steep slopes and permeable soils on low permeability rocks (Weiler and McDonnell, 2007; Anderson et al., 2009; Cammeraat and Kooijman, 2009). Compaction can affect this hierarchy, possibly resulting in a more heterogeneous spatial distribution of flow processes.

2.5. Mapping soil compaction

When assessing the effects of soil compaction on floods one would ideally like to know the spatial distribution and extent of soil compaction, or at least the soil compaction risk. A number of approaches have been developed for assessing the soil compaction risk although, invariably, they have focused on agricultural applications rather than floods. Van den Akker, (1988, 1994) computed soil stresses due to tractor wheels based on the relationships of Söhne (1958) by dividing the contact area into small units and aggregating the stresses from point loads of all units. Lebert (2010) estimated the soil compaction risk for the arable land in Germany using results of Houšková (2008), while Troldborg et al. (2013) used Bayesian belief networks by combining data from standard soil surveys, land use and expert judgement. D'Or and Destain (2014) computed the preconsolidation stress (determined based on the stress-strain relationship of soil obtained during laboratory compression according to Casagrande (1936)) from pedotransfer functions (Horn and Fleige, 2003), based on pedological, mechanical and hydraulic characteristics within a geostatistical framework. Recently, geophysical techniques for investigating subsurface compaction in agricultural soils have been advanced, such as ground penetrating radar (Lane et al., 2016, Wang et al., 2016, André et al., 2012), although these are usually limited to rather small scales. Mapping methods can be assisted by GPS based modelling of spatial patterns of field traffic intensity (Duttmann et al., 2013).

3. Experimental evidence of soil compaction effects on floods

3.1. Plot scale

Compaction of the topsoil due to tillage practices results in a reduced infiltration capacity and increases the probability of surface runoff formation during heavy precipitation (e.g., Byrd et al., 2002). Furthermore, the spatial variability of compaction due to the trafficked rows and non-trafficked interrows tends to enhance the spatial variability of surface and subsurface flow paths (Liebig et al., 1993; Mohanty et al., 1996). Kim et al. (2010) conducted field experiments on Mexico silt loam with field treatments of uniformly compacted and non-compacted plots. They found an increase in the bulk density of the compacted plot of 8%, and a decrease in saturated hydraulic conductivity of 69%, respectively, which would translate into increased surface runoff. Battiato et al. (2015) studied the effect of slipping driving wheels of agricultural equipment on surface runoff generation during sprinkling experiments. They found that the runoff coefficient increased from 0.79 with a minimum slip of 1% to 1.00 with a maximum slip of 27%, indicating that all the rainwater would be transformed into surface runoff at high slip.

The formation of a plough pan in the subsoil changes the direction of water percolation by impeding vertical infiltration and enhancing interflow. Bertolino et al. (2010), for instance, found that soils in South-eastern Brasilia with a plough pan at about 20 cm depth stay longer saturated after rainfall events and favour surface runoff during intense rainy periods. Singh and Hadda (2014) reported a decrease in the infiltration rate with increasing subsoil compaction. They observed a decrease in infiltration rate by a factor of 2.0–2.3 under two different treatments of their sandy loam soil. The decrease in infiltration rate and cumulative infiltration was due to a decrease in total porosity under higher subsoil compaction.

Using infiltration and dye tracer experiments, supplemented by soil textural and structural data, Alaoui et al. (2012) investigated flow pathways on grassland and forest hillslopes in order to identify the controls of surface runoff generation. They showed that the two types of land use lead to different flow processes, mainly vertical infiltration for the forest soil and mainly surface runoff for the grassland soil (Fig. 1). This is due to the larger root water uptake by trees, and thus lower soil moisture, and the larger unsaturated hydraulic conductivity of forest soils as compared to compacted grassland soils. The low efficiency of grassland soil macropores in transporting water vertically downward can be explained by (i) the fine and dense topsoil layers caused by the land use that limits water fluxes into the underlying macropores and (ii) their restricted number, their tortuosity, and the restricted interaction between macropores and the matrix below the topsoil layer. The larger root water uptake of forest soil as compared to grassland soil can be viewed as an additional factor enhancing its storage capacity (difference between total porosity and maximal soil moisture measured during infiltration) and, consequently, may reduce the generation of surface runoff. Storage capacity may provide key information on the strength of macropore flow and the interaction between macropores and the soil matrix that are highly sensitive to the degree of soil compaction (e.g., Alaoui, 2015).

3.2. Hillslope scale

At the hillslope scale, changes in the soil structure due to mechanical stresses resulting from tillage practices or cattle trampling can increase lateral fluxes in the topsoil (interflow) and surface runoff (Doerner and Horn, 2006). At the soil surface, structure-degraded or crusty soils caused by a lack of soil cover or by heavy

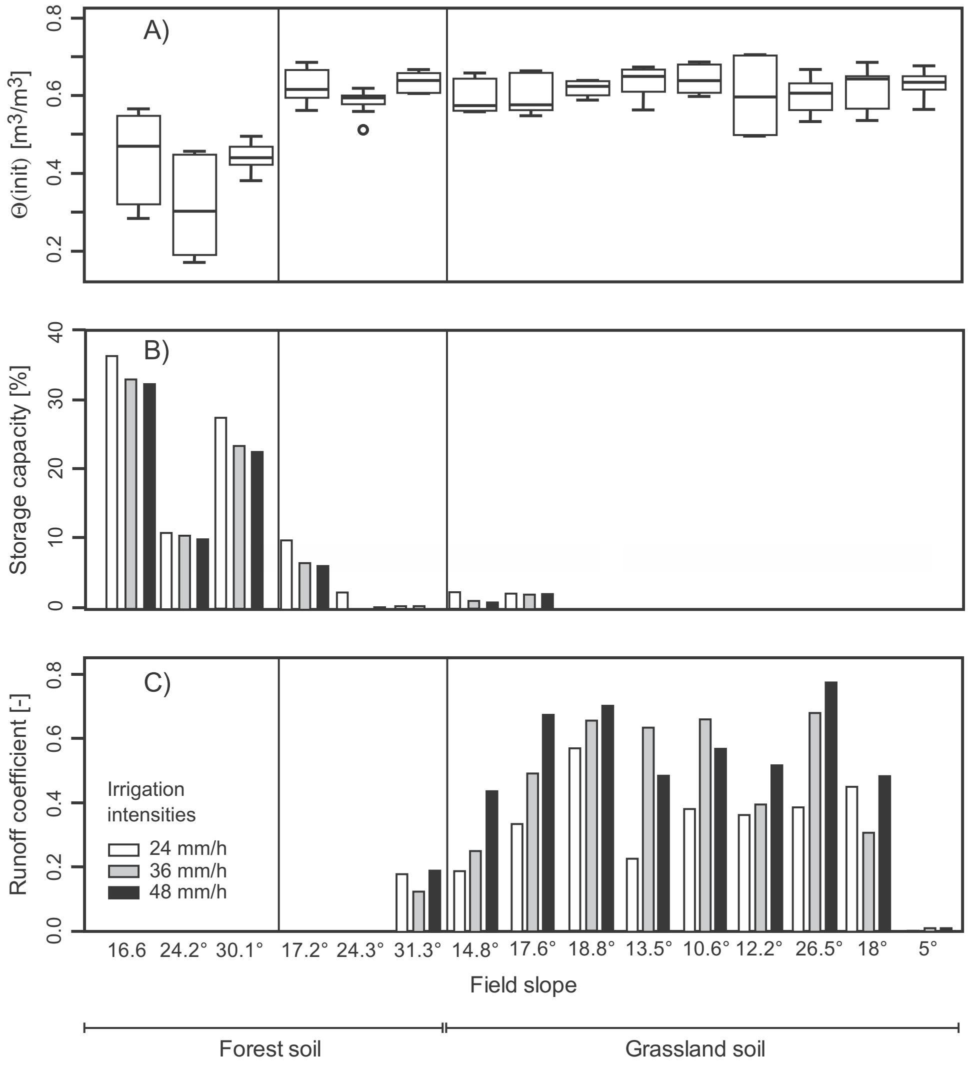


Fig. 1. Measured soil moisture variation before irrigation with median, upper and lower quartiles, outer fences, and outliers, confidence interval of 95% (A); storage capacity (B); and runoff coefficient specific to an individual irrigation (defined as surface runoff divided by the corresponding rainfall, both measured during one hour and expressed as depth over plot area in mm (C) for forest and grassland soils at plots in the Bernese Oberland, Switzerland. In A, each box contains 9 measurements at the topsoil during three irrigation intensities (Alaoui et al., 2012, modified).

agricultural machines, may lead to ponding of water or overland flow in sloping landscapes and potentially to increased erosion (Battiato et al., 2015). At the hillslope scale, the conditions that affect surface runoff generation have often been investigated using sprinkling experiments. Scherrer et al. (2007) conducted sprinkling experiments on 60 m^2 hillslope sites at 18, mainly grassland, locations in Switzerland with rates of 50–100 mm/h during 3–6 h. They found that infiltration inhibitors, such as compacted topsoils in combination with surface sealing, and permanently hydrophobic humus in combination with poor macropore development were linked to surface runoff excess in some locations. Attributes such as vegetation, slope, soil clay content and antecedent soil moisture were not directly linked to surface runoff excess. Other studies showed that compaction of water repellent, dry soils in forested catchments may lead to a 'temporary' Hortonian overland flow (e.g., Badoux et al., 2006; Schwarz, 1986; Kohl et al., 1997; Markart et al., 2004).

3.3. Catchment scale

The catchment evidence reported in the literature is mostly related to stock trampling effects (e.g., Holman et al., 2003; Pattison and Lane, 2011). Stocking densities have recently increased in a number of countries and this has been correlated with increasing floods. For example, in Wales, 72% of the agricultural land was under grassland production to support sheep farming in 2005. Sheep numbers in the UK increased from 19.7 million in 1950 to 40.2 million in 1990 (Fuller and Gough, 1999). Stock tends to reduce the vegetation cover, which may lead to soil surface crusting and reduced overland flow resistance (Ferrero, 1991). It may also lead to a decrease in evapotranspiration (Owens et al., 1997). Heathwaite et al. (1990) found that infiltration capacity was reduced by 80% on grazed areas compared to fields with no stock. Overall, stock trampling may impact on runoff generation and, possibly, downstream flood risk (Pattison and Lane, 2011). For example, in the Derwent catchment sheep stocking rates doubled between 1944 and 1975 which coincided with a runoff increase of 25% (Evans, 1996). Similarly, increasing flow peaks in the upper catchment of the River Lune was qualitatively related to increased stock densities (Orr and Carling, 2006). Within the Yorkshire Ouse catchment, over 40% of the sites investigated after the autumn 2000 floods had high soil degradation, and this was estimated to have caused a runoff increase of between 0.8% and 9.4% (Holman et al., 2003). Heathwaite et al. (1989) found that

7% of the rainfall was converted to runoff in ungrazed fields, while this increased to 53% in grazed fields.

Although urban soils are often thought to be of poor quality and highly compacted (Lorenz and Lal, 2009; Pickett and Cadenasso, 2009), little attention has been paid to its impact on floods (Edmondson et al., 2011). Arnold and Gibbons (1996) and White and Greer (2006) concluded that storm runoff and peak flow increase with urban development as the proportion of impervious land increases. For example, Mercer Creek, an urban stream in western Washington, had an earlier and higher peak discharge, and a larger volume, during a one-day storm on February 1, 2000 than Newaukum Creek, a nearly rural stream (Konrad, 2016). In general, runoff increases with the fraction of built-up area in a catchment, but the relationship is not necessarily linear (Chen et al., 2015). Importantly, the location of built-up area within the catchment matters because of spatial flow connectivity (Warburton et al., 2012; Sanyal et al., 2014).

4. Modelling evidence of soil compaction on floods

Numerous studies have attempted to relate land use changes and flood changes based on hydrological modelling (Table 2). In this review we have included studies that are not strictly on soil compaction but more generally on land use to put soil compaction into a broader context. The studies fall into three groups: (i) increasing areas of compacted soils (Grayson et al., 2010; Schilling et al., 2014a,b; Peña et al., 2016; Fohrer et al. 2001); (ii) changes in rainfall exacerbated by highly degraded and compacted soils (e.g., Viglione et al., 2016; Holman et al., 2003), and (iii) soil

Table 2
Modelling evidence of land use change and soil compaction effects on peak discharge at the catchment scale.

References	Model/ Approach	Catchment/area	Land use distribution	Data used and analysis	Main outcomes
Grayson et al. (2010)	Storm hydrograph data	Trou Beck (UK) (11.4 km^2)	Blanket peat: 75%	Weather station Gauging stations Hourly measurements of surface runoff at plot scale Soil properties obtained from a combination of data collected from previous study and visual soil examination	Peak flows are significantly higher and lag times shorter when blanket peat cover is reduced.
Schilling et al. (2014a, b)	SWAT model	Raccoon River watershed (USA) (9400 km^2)	Agricultural area with row crop of corn and soybean: 76%; agricultural grassland: 17%; forest: 4%; urban areas; water: 1%.	No direct measurements of soil properties were performed Soil layer data obtained from the Soil Survey Geographic database to characterize soil properties	Converting all cropland to perennial vegetation drastically reduced peak discharge. Converting half of the land to perennial vegetation or extended rotations reduced flooding potential.
Peña et al. (2016)	TETICS, conceptual distributed hydrological model	Combeima River catchment (Columbia) (217 km^2)	1) Grassland (increase by 37.5%): forest (decrease by 32.1%); crops decrease by 6.2%) from 1991 to 20002) Forest (increase by 7.0%); crops (increase by 55.9%); grassland (decrease by 30.5%)	No direct measurements of soil properties were performed (obtained using pedo-transfer function) Existing land use historical evolution Hydrometric station Weather stations	1) First changes in land use produced an increase of 2.1% of mean annual maximum flow. 2) secondary changes produced a 7.0% decrease in the maximum annual flows.
Fohrer et al. (2001)	SWAT model	Dietzhölze watershed (Germany) (82 km^2)	Forest: 55.4%; fallow area: 27.6%; grassland: 10.1%; field crop: 0.5%.	No direct measurements of soil properties were performed (crop, soil and tillage parameters were obtained from regional data sets and literature) Daily weather data Calibration and validation were performed using streamflow measurements	The decrease of forest due to an increase of grassland amplifies the peak flows and thus risk of flooding.
Viglione et al. (2016)	Finger printing attribution	97 catchments (Austria) (areas ranging from 10 to 79,500 km^2)	Intensification of agriculture with heavy machines (area not specified)	Hourly and daily precipitation data of 900 rainfall stations	Precipitation change is the main driver of increasing flood trends in Upper Austria. For small catchments, land use change plays an important role.
Holman et al. (2003)	SCS Runoff Curve Number (CN) method	4 catchments (UK): Ouse (4829 km^2); Severn (9753 km^2); Bourne 853 km^2); Uck (103 km^2)	Agricultural area (%): Ouse (71); Severn (73); Bourne (47); Uck (53). Related structural degradation mainly due to compaction may have occurred over 45% of the Severn, 30–35% of the Ouse and Uck, and 20% of the Bourne.	No direct measurements of soil properties were performed (detailed observations of soil horizon properties at the pedon scale) Soil structural degradation was qualitatively linked to the type of management system to illustrate the potential magnitude of the hydrological impact of the extrapolated soil structural degradation	Excess rapid response runoff during autumn floods of 2000 was related to the highly degraded and compacted soils in fodder maize fields (due to harvesting under wet soil conditions).
Roy and Mistri (2013)	Kinematic wave, SCS Curve Number Method	Kunur River Basin (India) (922.40 km^2)	Low infiltration rate with fine sandy loam, dense forest, and degraded wood: 55%; Fine clay to silt soil with agricultural land (35%); moderate infiltration rate with coarse texture land, pasture, and open scrap area (7%); urban area (3%)	No direct measurements of soil properties were performed Curve number of the watershed was obtained from Soil Conservation Service to link land use, soil characteristics and peak discharge	Peak flood discharge was mainly due to the low infiltration capacity of the fine material covering 55% of the basin (e.g., degraded wood land) and agricultural land (35%).

type effects, i.e. fine texture and low infiltration capacity of degraded forest and wood land soils (Roy and Mistri, 2013).

4.1. Area of compaction

Most studies reviewed found a direct relationship between increased area of compacted soil and peak discharge. Grayson et al. (2010) reported that the storm hydrograph in their 11.4 km^2 catchment was significantly affected by the area of bare peat, so revegetation of eroded blanket peatland could be beneficial in reducing flood peaks. Schilling et al. (2014a,b) suggest that land afforestation in the Raccoon River watershed could reduce both the number of flood events and the frequency of severe floods. Peña et al. (2016) analysed the relationship between changes in topsoil hydraulic properties (static storage capacity and saturated hydraulic conductivity) due to changes in land use and peak flows using a conceptual distributed hydrological model (Table 2). In their study, grassland area increased by 37.5% while forests and crops decreased by 32.1 and 6.2%, respectively, between the 1991 and 2000 scenarios. These changes produced an increase of 2.1% in the mean annual floods. In the 2007 scenario, forest and crop areas were increased by 7.0% and 55.9%, while grassland was decreased by 30.5% compared to the 2000 scenario which translated in a 7.0% decrease of the mean annual floods. Fohrer et al. (2001) used the SWAT (Soil and Water Assessment Tool) model to quantify the hydrologic response of several catchments to land use change and noted that a decrease in forest cover may amplify flood peaks for the Dietzhölze catchment in Germany.

The outcomes cited above are supported by other studies. Hess et al. (2010) modelled the impacts of improved soil conditions on peak discharges across England and Wales. They showed that changes in land management can reduce small floods while the effect on large flood peaks (100 year floods) is less than 5%. McIntyre and Marshall (2010) proposed that agriculturally improved grassland (which at some point had been drained, ploughed and fertilized) produces a flashier response than grassland in a more natural condition in the UK. Naef et al. (2002) modelled the effect of converting pasture to forest showing that fast-response dominant runoff processes may become slower. However, subsurface flow processes, occurring mainly in the deep soil layers or in the bedrock, are often outside the sphere of influence of land use change. Yan et al. (2013) attributed changes in streamflow to changes in the extent of farmland, forest and urban areas in a Chinese catchment while Chen et al. (2015) reported a direct relationship between rapid urbanisation and peak discharge.

4.2. Rainfall and compaction

While the studies mentioned above have focused on a single driver, a number of multidriver studies have been published recently. For example, Villarini and Strong (2014) and Prosdocimi et al. (2015) considered precipitation and a land use indicator as covariates in US and UK contexts, respectively. While Villarini and Strong (2014) attributed flood changes to rainfall variability changes, Prosdocimi et al. (2015) focused on the dominant role of urbanisation. Viglione et al. (2016) reported precipitation change to be the main driver of increasing flood trends in Upper Austria, while they identified land use change as an important driver in small catchments (Fig. 2). They reasoned that the effect of land use change on floods decreases with catchment area due to a shift in runoff generation mechanisms. In small catchments with short response times, floods are mostly generated by high intensity, short duration storms, so the infiltration excess mechanism is dominant. In large catchments with long response times, floods are mostly generated by low intensity, long duration storms, so the saturation excess mechanism is dominant. Since land use change affects the infiltration excess mechanism more strongly (through reduced infiltration capacity associated with soil compaction) than the saturation excess mechanism, the land use change effect on floods decreases with catchment area (Fig. 2). In their four UK catchments, Holman et al. (2003) showed that rapid response runoff during the autumn floods of 2000 was related to the widespread highly degraded and compacted soils in fodder maize fields due to harvesting under wet soil conditions. At larger catchment scales, agricultural land management does not seem to have affected flooding in the UK (O'Connell et al., 2007) which suggests that the effect of compaction does decrease with catchment area.

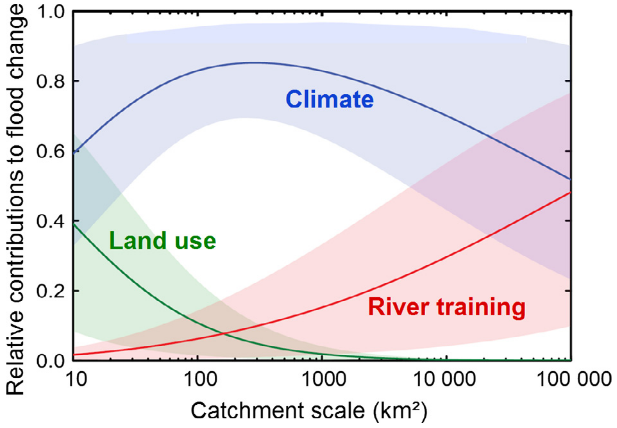


Fig. 2. Attribution of observed trends of mean annual floods in Upper Austria (1950–2012, 97 catchments) to land use change (intensification of agriculture with heavy machines), climate and river training, y axis is dimensionless (from Viglione et al., 2016).

4.3. Soil texture exacerbating compaction effects

The effect of compaction on increasing peak discharges may be enhanced if topsoils are fine textured with low infiltration capacities. Roy and Mistri (2013) showed a direct relationship between the extent of area covered by fine material and peak discharge in their Kunur watershed (India). Based on the hydrological soil groups, the areas with particularly large peak discharges were characterized by fine sandy loam, dense forest and degraded wood land (55%), followed by areas characterized by fine clay to silt soils and agricultural land use (35%). Similarly, Alaoui et al. (2011b) found that, compared to forest hillslopes, grassland hillslopes had higher micropore volumes in the topsoil down to 0.35 m. The topsoils of the hillslopes that generated surface runoff had higher clay contents than the hillslopes without surface runoff. As clay content was closely correlated with micropore volume, the authors concluded that the high clay content enhances matrix flow, delays water routing into the macropores, and thus increases surface runoff.

5. Research gaps

Research gaps on soil compaction effects on floods mainly remain at the medium and large catchment scales, and in particular regarding the question whether the effects really decrease with area and why. We consider the following to be key research gaps.

5.1. Areal coverage

A first order control of the effect on floods is the total area of soil compaction within a catchment which, however, can vary tremendously in space and time depending on agricultural practices (Fiener et al., 2011; Green et al., 2003). Methods are needed to reliably map soil compaction in the landscape. These may be based on a combination of field surveys, spatial soil data and, possibly, remote sensing.

5.2. Patchiness/Connectivity

The spatial arrangement of compacted soils may be equally important as their area per se. This is because of the role of spatial connectivity and patchiness on runoff generation and routing from the hillslope to the catchment scales (Western et al., 1998). A better understanding of the effects of connectivity and location would be useful for deriving scaling relationships for upscaling land-use change effects to the catchment scale.

5.3. Temporal variability

The seasonal variability in topsoil compaction due to regular agricultural practices such as harvesting and subsequent field traffic is important for flood generation, if maximum rainfall coincides with maximum compaction during the year. Current models do not account for this variability. More research is needed on understanding these links across scales.

5.4. Feedbacks

Many of the processes involved in compaction effects on floods are interlinked (Rogger et al., 2017). For example, the mechanical and hydraulic processes during soil deformation are coupled, which exacerbates soil compaction since more compact soils generally remain wet for a longer time of the year. Identifying the most important feedbacks related to soil compaction processes is therefore of key interest for upscaling their impacts to the catchments scale.

5.5. Masking

In most instances, changes in floods at the catchment scale are related to more than one control, including climate and river training. Quantitative knowledge of these components is necessary to isolate the impact of soil compaction on floods. Blöschl et al. (2007) and Viglione et al. (2016), among others, suggested that the impact of land use on floods decreases with catchment scale, but more quantitative analyses in different climates are needed to attribute flood changes to their drivers including soil compaction.

5.6. Model parameterization

Studies on land-use change impacts at the catchment scale currently are mostly modelling studies that are based on assumptions of how model parameters change with changing land-use (e.g. Salazar et al., 2012). An important task is to improve soil compaction parameterization at the hillslope and catchment scales. The parameterizations should account for flow connectivity and patchiness.

6. Ways forward

We believe that the research gaps summarised above can be addressed by focusing on four research strands: (i) synthesizing past research related to soil compaction and runoff by meta analyses, (ii) complementing this knowledge by additional field experiments, (iii) developing novel methods for mapping soil compaction, and (iv) learning from disciplines such as agricultural sciences and soil physics where extensive knowledge on soil compaction exists.

6.1. Meta analyses

As suggested by Rogger et al. (2017) comparative meta analyses of existing studies related to soil compaction and runoff processes would be a first step towards generalising the findings from individual case studies (see, e.g., Koricheva and Gurevitch, 2014; Mutema et al., 2015). Soil compaction studies have often been performed in agricultural contexts, but do address very relevant information related to flood processes such as changes in pore structure, hydraulic conductivity and bulk density. To facilitate future meta-analyses it would be important for publications to fully report the relevant information, ideally in a consistent way (Koutsoyiannis et al., 2016). Data on soil physical properties measured in the field, compaction assessments and maps of compaction susceptibility of soils should be made publically available in a similar way as the European Hydropedological Data Inventory (EU-HYDI, Tóth et al., 2013) and the HYPRES-database (Wösten et al., 1999).

6.2. Additional field experiments

Existing long-term experimental sites should be upgraded to better address the question of soil compaction effects on floods. Specifically, the evolution of hydraulic soil characteristics and its dynamics during the year, including changes in the macropore volume, connectivity and functionality, should be monitored over long periods of time in addition to runoff. Of particular interest is the memory effect of soils, i.e. how fast a change in soil conditions translates into a corresponding change in flood characteristics. In order to obtain a mechanistic description of the coupled mechanical and hydraulic processes, tailored field experiments should be conducted. These would consist of treatment and wheeling experiments on plots under different crop management practices and soils, where soil deformation and stress-strain processes are measured as well as the stress induced changes in hydraulic conductivity and their time dependency during loading and soil deformation. This research should build on the findings of the meta-analyses mentioned above.

6.3. Mapping soil compaction

There is a lot of potential in developing new mapping methods that may assist in understanding the spatial compaction patterns and thus upscaling compaction effects to the catchment scale (Blöschl, 2006). Data from geophysical techniques such as ground penetrating radar (Lane et al., 2016), GPS based modelling of field traffic (Duttmann et al., 2013) and perhaps remote sensing data (e.g., Ryan et al., 2014; Joshi et al., 2016) could be combined. Since soil compaction may persist over decades, knowledge of the land use history would be a benefit.

6.4. Bridging gap between different disciplines

Collaborations between hydrology and sister disciplines has dramatically increased in the recent decade, but there is room for improvement in particular regarding soils. Bringing soil science, pedology, agricultural sciences and hydrology closer together through joint projects, conferences and publications would assist in a more permanent contribution to advancing science. Batey (2009) noted that "*several authors recommend that monitoring of soil physical conditions, including compaction should be part of routine soil management*". We suggest that monitoring compaction processes would also be of enormous benefit for water management.

7. Conclusions

Based on the literature review, we can distinguish three ways in which soil compaction impacts peak discharge at the catchment scale: (i) by an increase in the area affected by soil compaction; (ii) by changes in rainfall events, exacerbated by highly degraded soils; and (iii) by coincidence of soil compaction with fine topsoils in degraded lands. More specifically, the following conclusions can be drawn on the effects of soil compaction on floods:

1. Experimental studies at the plot and hillslope scales suggest consistent evidence of the impact of soil compaction on increasing surface runoff. Locally, compaction tends to reduce infiltration and increase surface runoff. With increasing scale, the tendency of reduced infiltration and increased surface runoff persists, but is modulated by numerous other factors such as surface sealing, permanently hydrophobic humus, and poor macropore development. At the catchment scale, studies tend to be more speculative as most of the evidence comes from non quantitative reasoning. Increasing floods in some regions were attributed to increased stocking densities, as suggested by marked differences of surface runoff between grazed and ungrazed fields. The literature suggests that storm runoff increases with urban development as the proportion of impervious land increases, but this relationship is not necessarily linear. The location of built-up area within the mosaic of land uses may affect the spatial flow connectivity and consequently surface runoff in many ways.
2. Modelling studies suggest that soil compaction may affect peak discharges at the catchment scale, but the magnitude of this effect varies between studies. In small catchments with short response times, floods are mostly generated by the infiltration excess mechanism from high intensity, short duration storms. In this case, the reduction of infiltration capacity by soil compaction can have a major effect on flood peaks. In large catchments, where floods are often produced by the saturation excess mechanism from lower intensity, longer duration storms, the effect of soil compaction of flood peaks is less obvious. Overall, soil compaction effects on floods tend to increase with the size of the compacted area, but its spatial arrangement in the landscape does matter.
3. Research gaps include the reliable mapping of soil compaction in the landscape, understanding the patchiness of compacted soils and the spatial connectivity of flow paths. They also include a better understanding of the temporal variability of compacted soil characteristics, feedbacks between floods and soil compaction at different time scales, and unravelling the multitude of factors that may mask the relationship between soil compaction and floods. Future research and funding should give high priority to understanding the links between soil compaction and floods at the catchment scale, as it will provide key information on one of the important drivers of floods.

Acknowledgements

The present work was developed within the framework of the Panta Rhei Research Initiative of the International Association of Hydrological Sciences (IAHS) as a contribution of the Working Groups “Understanding Flood Changes” and “Changes in Flood Risk.” Funding was partly provided by the Austrian Science Foundation (FWF projects I 3174-N29 and P 23723-N21), the SYSTEM-RISK project (EU grant 676027) and the European Research Council, Flood Change project (ERC advanced grant 291152). We also would like to thank the handling editor as well as the three reviewers for their constructive comments which considerably improved this paper.

References

Addiscott, T.M., Mirza, N.A., 1998. Modelling contaminant transport at catchment or regional scale. Environ. Manage. 27 (1), 211–221.

Alakukku, L., 1996. Persistence of soil compaction due to high axle load traffic: I. Short-term effects on the properties of clay and organic soils. Soil Till. Res. 37, 211–222.

Alaoui, A., 2015. Modelling susceptibility of grassland soil to macropore flow. J. Hydrol. 525, 536–546. https://doi.org/10.1016/j.jhydrol.2015.04.016.

Alaoui, A., Helbling, A., 2006. Evaluation of soil compaction using hydrodynamic water content variation: comparison between compacted and non-compacted soil. Geoderma 134, 97–108.

Alaoui, A., Lipiec, J., Gerke, H.H., 2011a. A review of the changes in the soil pore system due to soil deformation: A hydrodynamic perspective. Soil Tillage Res. 115–116, 1–15.

Alaoui, A., Caduff, U., Gerke, H.H., Weingartner, R., 2011b. Preferential flow effects on infiltration and runoff in grassland and forest soils. Vadose Zone J. 10, 367–377.

Alaoui, A., Spiess, P., Beyeler, M., Weingartner, R., 2012. Up-scaling surface runoff from plot to catchment scale. Hydrol. Res. 43 (4). https://doi.org/10.2166/nh.2012.057.

Anderson, S.H., Udawatta, R.P., Seobi, T., Garrett, H.E., 2009. Soil water content and infiltration in agroforestry buffer strips. Agrofor. Syst. 75, 5–16.

André, F., van Leeuwen, C., Saussez, S., Van Durmen, R., Bogaert, P., Moghadas, D., de Rességuier, L., Delvaux, B., Vereecken, H., Lambot, S., 2012. High-resolution imaging of a vineyard in south of France using ground-penetrating radar, electromagnetic induction and electrical resistivity tomography. J. Appl. Geophys. 78, 113–122.

Arnold Jr., C.L., Gibbons, C.J., 1996. Impervious surface coverage: the emergence of a key environmental indicator. J. Am. Plann. Assoc. 62 (2), 243–258.

Arvidsson, J., Trautner, A., van den Akker, J.J.H., Schjønning, Per, 2001. Subsoil compaction caused by heavy sugarbeet harvesters in southern Sweden: II. Soil displacement during wheeling and model computations of compaction. Soil and Tillage Res. 60 (1–2), 79–89. https://doi.org/10.1016/S0167-1987(01)00168-4. ISSN 0167-1987.

Arvidsson, J., Trautner, A., Keller, T., 2002. Influence of Tyre Inflation Pressure on Stress and Displacement in the Subsoil. In: Pagliai, M., Jones, R. (Eds.), Sustainable Land Management – Environmental Protection. A Soil Physical Approach, Advances in Geoecology, 35. Catena Verlag, GeoEcology, Reiskirchen, Germany, pp. 331–338.

Badoux, A., Witzig, J., Germann, P.F., Kienholz, H., Lüscher, P., Weingatner, R., Hegg, Ch., 2006. Investigations on the runoff generation at the profile and plot scales, Swiss Emmental. Hydrol. Process. 20, 377–394.

Bakker, D.M., Davis, R.J., 1995. Soil deformation observations in a Vertisol under field traffic. Aust. J. Soil Res. 33, 817–832.

Balbuena, R.H., Terminiello, A.M., Claverie, J.A., Casado, J.P., Marlats, R., 2000. Soil compaction by forestry harvester operation. Evolution of physical properties. Revista Brasileira de Engenharia Agricola e Ambiental 4, 453–459 (in Spanish).

Batey, T., 2009. Soil compaction and soil management – a review. Soil Use Manag. 25, 335–345.

Batey, T., McKenzie, M., 2006. Soil compaction: identification directly in the field. Soil Use Manage. 22, 123–131.

Battiato, A., Alaoui, A., Diserens, E., 2015. Impact of normal and shear stresses due to wheel slip on hydrological properties of an agricultural clay loam: experimental and new computerized approach. J. Agricul. Sci. 7 (4), 1–15.

Battiato, A., Diserens, E., Laloui, L., Sartori, L., 2013. A mechanistic approach to topsoil damage due to slip of tractor tyres. J. Agric. Sci. Appl. 2 (3), 160–168.

Berisso, F.E., Schjønning, P., Keller, T., Lamandé, M., Etana, A., de Jonge, L.W., Iversen, B.V., Arvidsson, J., Forkman, J., 2012. Persistent effects of subsoil compaction on pore size distribution and gas transport in a loamy soil. Soil Tillage Res. 122, 42–51. https://doi.org/10.1016/j.still.2012.02.005. ISSN 0167-1987.

Bertolino, A.V.F.A., Fernandes, N.F., Miranda, J.P.L., Souza, A.P., Lopes, M.R.S., Palmieri, F., 2010. Effects of plough pan development on surface hydrology and on soil physical properties in Southeastern Brazilian plateau. J. Hydrol. 393, 94–104. https://doi.org/10.1016/j.jhydrol.2010.07.038. ISSN 0022-1694.

Birkas, M., 2008. Environmentally sound adaptable tillage. Akademia Kiado, Budapest, Hungary.

Blöschl, G., Ardoin-Bardin, S., Bonell, M., Dorninger, M., Goodrich, D., Gutknecht, D., Matamoros, D., Merz, B., Shand, P., Szolgay, J., 2007. Atwhat scales do climate variability and land cover change impact on flooding and low flows? Hydrol. Processes 21, 1241–1247. https://doi.org/10.1002/hyp.6669.

Blöschl, G., 2006. Hydrologic synthesis - across processes, places and scales. Special section on the vision of the CUAHSI National Center for Hydrologic Synthesis (NCHS). Water Resour. Res. 42. article number W03S02.

Blöschl, G., Hall, J. Parajka, R. A. P. Perdigão, B. Merz, B. Arheimer, G. T. Aronica, A. Bilibashi, O. Bonacci, M. Borga, I. Canjevac, A. Castellarin, G. B. Chirico, P. Claps, K. Fiala, N. Frolova, L. Gorbachova, A. Gül, J. Hannaford, S. Harrigan, M. Kireeva, A. Kiss, T. R. Kjeldsen, S. Kohnová, J. J. Koskela, O. Ledvinka, N. Macdonald, M.

Mavrova-Guirguinova, L. Mediero, R. Merz, P. Molnar, A. Montanari, C. Murphy, M. Osuch, V. Ovcharuk, I. Radevski, M. Rogger, J. L. Salinas, E. Sauquet, M. Šraj, J. Szolgay, A. Viglione, E. Volpi, D. Wilson, K. Zaimi and N. Živkovic, 2017. Changing climate shifts timing of European floods. Science, 357 (6351) 588–590, doi: 10.1126/science.aan2506.

Blöschl, G., Sivapalan, M., 1995. Scale issues in hydrological modelling – a review. Hydrol. Process. 9, 251–290.

Bodner, G., Scholl, P., Loiskandl, W., Kaul, H.-P., 2013. Environmental and management influences on temporal variability of near saturated soil hydraulic properties. Geoderma 204–205, 120–129.

Botta, G., Jorajuria, D., Rosatto, H., Ferrero, C., 2006. Light tractor traffic frequency on soil compaction in the Rolling Pampa region of Argentina. Soil Till. Res. 86, 9–14.

Boone, F.R., 1988. Weather and other environmental factors influencing crop responses to tillage and traffic. Soil Till. Res. 11, 283–324.

Brewer, R., 1964. Fabric and Mineral Analysis of Soils. John Wiley and Sons (Eds), New York. 482 pp.

Byrd, E.J., Kolka, R.K., Warner, R.C., Ringe, J.M. 2002. Soil Water Percolation and Erosion on Uncompacted Surface Mine Soil in Eastern Kentucky. In: National Meeting of the American Society of Mining and Reclamation, Lexington, KY, June 9-13, 2002. Published by ASMR, 3134 Montavesta Rd., Lexington, KY, 40502.

Cambi, M., Certini, G., Neri, F., Marchi, E., 2015. The impact of heavy traffic on forest soils: A review. Forest Ecology Manage. 338, 124–138.

Cammeraat, E.L.H., Kooijman, A.M., 2009. Biological control of pedological and hydrogeomorphological processes in a deciduous forest ecosystem. Biologia 64, 428–432.

Carroll, Z.L., Reynolds, B. Emmett, B.A., Sinclair, F.L., Ruiz de Ona, C., Williams, P. 2004. The effect of stocking density on soil in upland Wales. Report to Country Council for Wales Report FC 73-02-280. No 630, Centre for Ecology and Hydrology.

Casagrande, A., 1936. The determination of the pre-consolidation load and its practical significance. In: Proceedings of the international conference on soil mechanics and foundation engineering. Harvard University Cambridge, pp. 60–64.

Chen, X., Tian, C., Xu, X., Meng Q, Cui, G., Zhang, Q. Xiang, L., 2015. Analyzing the effect of urbanization on flood characteristics at catchment levels Proc. IAHS 370 2015 33 38 10.5194/piahs-370-33-2015.

da Silva, A.P., Kay, B.D., Perfect, E., 1994. Characterization of the least limiting water range of soils. Soil Sci. Soc. Am. J. 58, 1775–1781.

Dexter, A.R., 1988. Advances in characterization of soil structure. Soil Till. Res. 11, 199–238.

Dexter, A.R., Czyz, E.A., Richard, G., Reszkowska, A., 2008. A user-friendly water retention function that takes account of the textural and structural pores spaces in soil. Geoderma 143, 243–253.

Dickerson, B.P., 1976. Soil compaction after tree-length skidding in northern Mississippi. Soil Sci. Soc. Am. J. 40, 965–966.

Doerner, J., Horn, R., 2006. Anisotropy of pore functions in structured Stagnic Luvisols in the Weichselian moraine region in N Germany. J. Plant Nutr. Soil Sci. 169, 213–220. https://doi.org/10.1002/jpln.200521844.

D'Or, D., Destain, M.F., 2014. Toward a tool aimed to quantify soil compaction risks at a regional scale: Application to Wallonia (Belgium). Soil Till. Res. 144, 53–71.

Dumbeck, G., 1984. Einfluss aussergewöhnlicher Druckbelastung auf das Bodengefüge und die Durchwurzelung. Mitteilungen der Deutschen Bodenkundlichen Gesellschaft 40, 61–62.

Duttmann, R., Brunotte, J., Bach, M., 2013. Spatial analyses of field traffic intensity and modeling of changes in wheel load and ground contact pressure in individual fields during a silage maize harvest. Soil Tillage Res. 126, 100–111.

Earl, R., 1997. Prediction of trafficability and workability from soil moisture deficit. Soil Till. Res. 40, 155–168.

Edmondson, J.L., Davies, Z.G., McCormack, S.A., Gaston, K.J., Leake, J.R., 2011. Are soils in urban ecosystems compacted? A citywide analysis. Biol. Lett. 7, 771–774.

Etana, A. et al., 2013. Persistent subsoil compaction and its effects on preferential flow patterns in a loamy till soil. Geoderma 192, 430–436.

Evans, R., 1996. Soil Erosion and its Impacts in England and Wales. Friends of the Earth, London, p. 121.

Ferrero, A.F., 1991. Effect of compaction simulating cattle trampling on soil physical characteristics in woodland. Soil Till. Res. 19, 319–329.

Fiener, P., Auerswald, K., Van Oost, K., 2011. Spatio-temporal patterns in land use and management affecting surface runoff response of agricultural catchments – a review. Earth-Sci. Rev. 106, 92–104.

Foley, J.A., DeFries, R., Asner, G.P., Barford, C., Bonan, G., Carpenter, S.R., Chapin, F.S., Coe, M.T., Daily, G.C., Gibbs, H.K., Helkowski, J.H., Holloway, T., Howard, E.A., Kucharik, C.J., Monfreda, C., Patz, J.A., Prentice, C., Ramankutty, N., Snyder, P.K., 2005. Global consequences of land use. Science 309, 570. https://doi.org/10.1126/ science.1111772.

Fohrer, N., Haverkamp, S., Eckhardt, K., Frede, H.G., 2001. Hydrologic response to land use changes on the catchment scale. Phys. Chem. Earth. 26, 577–582.

Froehlich, H.A., 1979. Soil compaction from logging equipment: effects on growth of young ponderosa pine. J. Soil Water Conserv. 34, 276–278.

Fuller, R.J., Gough, S.J., 1999. Changes in sheep numbers in Britain: implications for bird populations. Biol. Conserv. 91, 73–89.

Gerke, H.H., 2006. Preferential flow description for structured soils. J. Plant Nutr. Soil Sci. 169, 382–400.

Gill, W.R., Vanden Berg, G.E., 1967. Soil Dynamics in Tillage and Traction, 316. Agricultural Research Service, U.S.D.A., p. 511.

Grayson, R., Holden, J., Rose, R., 2010. Long-term change in storm hydrographs in response to peatland vegetation change. J. Hydrol. 389, 336–343.

Greacen, E.L., Sands, R., 1980. A review of compaction of forest soils. Aust. J. Soil Res. 18, 163–189.

Green, T.R., Ahuja, L.R., Benjamin, J.G., 2003. Advances and challenges in predicting agricultural management effects on soil hydraulic properties. Geoderam 116, 3–27.

Greenwood, K.L., McKenzie, B.M., 2001. Grazing effects on soil physical properties and the consequences for pastures: a review. Aust. J. Exp. Agric. 41, 1231–1250.

Hadas, A., 1987. Long-term tillage practice effects on soil aggregation modes and strength. Soil Sci. Soc. Am. J. 51, 191–197.

Håkansson, I., Lipiec, J., 2000. A review of the usefulness of relative bulk density values in studies of soil structure and compaction. Soil Till. Res. 53, 71–85.

Hall, J., Arheimer, B., Borga, M., Brázdil, R., Claps, P., Kiss, A., Kjeldsen, T.R., Kriaučiūnienė, J., Kundzewicz, Z.W., Lang, M., Llasat, M.C., Macdonald, N., McIntyre, N., Mediero, L., Merz, B., Merz, R., Molnar, P., Montanari, A., Neuhold, C., Parajka, J., Perdigão, R.A.P., Plavcová, L., Rogger, M., Salinas, J.L., Sauquet, E., Schär, C., Szolgay, J., Viglione, A., Blöschl, G., 2014. Understanding flood regime changes in europe: a state of the art assessment. Hydrol. Earth Syst. Sci. 18, 2735–2772. https://doi.org/10.5194/hess-18-2735-2014.

Hamza, M.A., Anderson, W.K., 2005. Soil compaction in cropping systems. A review of the nature, causes and possible solutions. Soil Tillage Res. 82, 121–145.

Hartge, K.H., Bohne, H., 1983. Effect of pore geometry on compressibility of soil and development of rye seedings. Z.f. Kulturtechnik und Flurbereinigung 24, 5–10.

Heathwaite, A.L., Burt, T.P., Trudgill, S.T., 1989. Runoff, sediment, and solute delivery in agricultural drainage basins - a scale dependent approach. In: Ragone, S. (Ed.), Regional characterization of water *quality*. IAHS Publ., pp. 175–191.

Heathwaite, A.L., Burt, T.P., Trudgill, S.T., 1990. Land-use controls on sediment production in a lowland catchment, south-west England. In: Boardman, J., Foster, I.D.L., Dearing, J.A. (Eds.), Soil Erosion on Agricultural Land. John Wiley and Sons, Ltd., Chichester, UK, pp. 70–86.

Hendrickx, J.M.H., Flury, M., 2001. Uniform and preferential flow mechanisms in the vadose zone. In: Conceptual models of flow and transport in the fractured vadose zone. National Academy Press, Washington D.C, pp. 149–187.

Hess, T.M., Holman, I.P., Rose, S.C., Rosolova, Z., Parrott, A., 2010. Estimating the impact of rural land management changes on catchment runoff generation in England and Wales. Hydrol. Process. 24, 1357–1368.

Hills, R.C., 1971. Lateral flow under cylinder infiltrometers–a graphical correction procedure. J. Hydrol. 13, 153–162.

Holman, I.P., Hollis, J.M., Bramley, M.E., Thompson, T.R.E., 2003. The contribution of soil structural degradation to catchment flooding: a preliminary investigation of the 2000 floods in England and Wales. Hydrol. and Earth Syst. Sci. 7 (5), 754–765.

Horn, R., 1988. Compressibility of arable land. Catena Supp 11, 53–71.

Horn, R., Domżał, H., Słowińska-jurkiewicz, A., van Ouwerkerk, C., 1995. Soil compaction processes and their effects on the structure of arable soils and the environment. Soil Tillage Res. 35, 23–36.

Horn, R., Fleige, H., 2003. A method for assessing the impact of load on mechanical stability and on physical properties of soils. Soil Tillage Res. 73, 89–99.

Horn, R., Rostek, J., 2000. Subsoil compaction processes-state of knowledge. Adv. Geoecol. 32, 4–54.

Horn, R., Way, T., Rostek, J., 2003. Effect of repeated tractor wheeling on stress/strain properties and consequences on physical properties in structured arable soils. Soil Till. Res. 73, 101–106.

Houšková, B., 2008. The Natural Susceptibility of Soils to Compaction. Office for the Official Publications of the European Communities, Luxembourg.

Hümann, M., Schüler, G., Müller, C., Schneider, R., Johst, M., Caspari, T., 2011. Identification of runoff processes – The impact of different forest types and soil properties on runoff formation and floods. J. Hydrol. 409, 637–649. https://doi.org/10.1016/j.jhydrol.2011.08.067.

Jakobsen, B.F., 1983. Persistence of compaction effects in a forest Kraznozem. Aust. For. Res. 13, 305–308.

Jarvis, N.J., Moeys, J., Koestel, J., Hollis, J.M., 2012. Preferential flow in a pedological perspective. In: Lin, H. (Ed.), Hydropedology: Synergistic integration of soil science and hydrology. Academic Press, Waltham, MA, pp. 75–120. https://doi.org/10.1016/B978-0-12-386941-8.00003-4.

Jégou, D., Brunotte, J., Rogasik, H., Capowiez, Y., Diestel, H., Schrader, S., Cluzeau, D., 2002. Impact of soil compaction on earthworm burrow systems using X-ray computed tomography: preliminary study. Eur. J. Soil Biol. 38, 329–336.

Jim, C.Y., 1998. Urban soil characteristics and limitations for landscape planting in Hong Kong. Landsc Urban Plan 40 (4), 235–249.

Jones, R.J.A., Spoor, G., Thomasson, A.J., 2003. Vulnerability of subsoils in Europe to compaction: a preliminary analysis. Special Issue of Soil & Tillage Res. on Subsoil Compaction. Soil Till. Res. 73, 131–143.

Joshi, N., Baumann, M., Ehammer, A., Fensholt, R., Grogan, K., Hostert, P., Jepsen, M., Kuemmerle, T., Meyfroidt, P., Mitchard, E., Reiche, J., Ryan, C., Waske, B., 2016. A review of the application of optical and radar remote sensing data fusion to land use mapping and monitoring. Remote Sens. 8, 70. https://doi.org/10.3390/rs8010070.

Kay, B.D., 1990. Rates of change of soil structure under different cropping systems. Adv. Soil Sci. 12, 1–52.

Kellner, E., Hubbart, J., 2016. Agricultural and forested land use impacts on floodplain shallow groundwater temperature regime. Hydrol. Process. 30, 625–636. https://doi.org/10.1002/hyp.10645.

Kim, H., Anderson, S.H., Motavalli, P.P., Gantzer, C.J., 2010. Compaction effects on soil macropore geometry and related parameters for an arable field. Geoderma 160, 244–251.

Kluitenberg, G.J., Horton, R., 1990. Effect of solute application method on preferential transport of solutes in soils. Geoderma 46, 283–297.

Kohl, B., Markart G., 2002. Dependence of surface runoff on rain intensity. In: Proceedings of the International Conference on Flood Estimation, March 6-8, Berne, Switzerland, 139–146

Kohl, B., Markart, G., Stary, U., Proske, H., Trinkaus, P., 1997. Abfluss-und Infiltrationsverhalten von Böden unter Fichtenalbeständen in der Gleinalm (Stmk.) [Drainage and infiltration characteristics of spruce forest soils in the 'Gleinalm' alp (Steiermark)]. Berichte der Forstlichen Bundesversuchsanstalt Wien 96, 27–32.

Konrad, C.P., 2016. Effects of Urban Development on Floods. U.S. Geological Survey (USGS) Fact Sheet 076-03. https://pubs.usgs.gov/fs/fs07603/

Koricheva, J., Gurevitch, J., 2014. Uses and misuses of meta-analysis in plant ecology. J. Ecol. 102 (4), 828–844.

Koutsoyiannis, D., Blöschl, G., Bárdossy, A., Cudennec, C., Hughes, D., Montanari, A., Neuweiler, I., Savenije, H., 2016. Joint editorial: Fostering innovation and improving impact assessment for journal publications in hydrology. J. Hydrol. 537, A1–A4.

Krümmelbein, J., Wang, Z., Zhao, Y., Peth, S., Horn, R., 2006. Influence of various grazing intensities on soil stability, soil structure and water balance of grassland soils in Inner Mongolia, P.R. China. In: Horn, R., Fleige, H., Peth, S., Peng, X. (Eds.), Soil management for sustainability, Advances in GeoEcology, vol. 38. Catena Verlag, Reiskirchen, pp. 93–101.

Kundzewicz, Z., Pinskwar, I., Brakenridge, G.R., 2017. Changes in river flood hazard in Europe: a review. Hydrol. Res. https://doi.org/10.2166/nh.2017.016.

Lane, A.L., Peterson, P.G., Hedley, C.B., McColl, S.T., Fuller, I.C., 2016. Using ground penetrating radar to map soil drainage patterns to improve irrigation efficiency. In: Currie, L.D., Singh, R. (Eds.), Integrated nutrient and water management for sustainable farming. http://flrc.massey.ac.nz/publications.html. Occasional Report No. 29. Fertilizer and Lime Research Centre, Massey University, Palmerston North, New Zealand. 10p.

Larsbo, M., 2011. An episodic transit time model for quantification of preferential solute transport. Vadose Zone J. 10, 378–385.

Lebert, M., 2010. Entwicklung eines Prüfkonzeptes zur Erfassung der tatsächlichen Verdichtungsgefährdung landwirtschaftlich genutzter Böden. Report, Umweltbundesamt, Germany, http://www.uba.de/uba-info-medien/4027.html.

Li, X., Zhang, L.M., 2009. Characterization of dual-structure pore-size distribution of soil. Can. Geotech. J. 46, 129–141.

Liebig, M.A. et al., 1993. Controlled wheel traffic effects on soil properties in ridge tillage. Soil Sci. Soc. Am. J. 57 (4), 1061–1066.

Lorenz, K., Lal, R., 2009. Biochemical C and N cycles in urban soils. Environ. Int. 35, 1–8. https://doi.org/10.1016/j.envint.2008.05.006.

Mace Jr., A.C., 1971. Recovery of forest soils from compaction by rubber-tired skidders. Minnesota Forestry Research Notes No. 266. University of Minnesota, St. Paul.

Mapa, R.B., Green, R.E., Santo, L., 1986. Temporal variability of soil hydraulic properties with wetting and drying subsequent to tillage. Soil Sci. Soc. Am. J. 50, 1133–1138.

Markart, G., Kohl, B., Sotier, B., Schauer, T., Bunza, G. Stern, R., 2004. Provisorische Geländeanleitung zur Abschätzung des Oberflächenabflussbeiwertes auf alpinen Boden-/ Vegetationseinheiten bei konvektiven Starkregen [A simple Code of Practice for Assessment of Surface Runoff Coefficients for Alpine Soil-/ Vegetation Units in Torrential Rain] (Version 1.0). BFW Dokumentationen. Bundesamt und Forschungszentrum für Wald, Wien.

McGrath, G.S., Hinz, C., Sivapalan, M., 2009. A preferential flow leaching index. Water Resour. Res. 45, W11405. https://doi.org/10.1029/2008WR007265.

McIntyre, N., Marshall, M., 2010. Identification of rural land management signals in runoff response. Hydrol. Proc. 24, 3521–3534.

Milne, R.M., Haynes, R.J., 2004. Comparative effects of annual and permanent dairy pastures on soil physical properties in the Tsitsikamma region of South Africa. Soil Use Manage. 20, 81–88.

Mohanty, B.P., Horton, R., Ankeny, M.D., 1996. Infiltration and macroporosity under a row crop agricultural field in a glacial till soil 1. Soil science 161 (4), 205–213.

Munkholm, L.J., Schjønning, P., Rasmussen, K.J., Tanderup, K., 2003. Spatial and temporal effects of direct drilling on soil structure in the seedling environment. Soil Tillage Res. 71, 163–173.

Mutema, M., Chaplot, V., Jewitt, G., Chivenge, P., Blöschl, G., 2015. Annual water, sediment, nutrient, and organic carbon fluxes in river basins: A global meta-analysis as a function of scale. Water Resour. Res. 51, 8949–8972. https://doi.org/10.1002/2014WR016668.

Nawaz, M.F., Bourrié, G., Trolard, F., 2013. Soil compaction impact and modelling. A review. Agron. Sustain. Dev. 33, 291–309.

Naef, F., Scherrer, S., Weiler, M., 2002. A process based assessment of the potential to reduce flood runoff by land use change. J. Hydrol. 267, 74–79.

Nie, Z.N., Ward, G.N., Michael, A.T., 2001. Impact of pugging by dairy cows on pastures and indicators of pugging damage to pasture soil in south-western Victoria. Aust. J. Agricul. Res. 52 (1), 37–43.

O'Connell, P.E.O., Beven, K., Carney, J.N., Clements, R.O., Ewen, J., Fowler, H., Harris, G., Hollis, J., Morris, J., O'Donnell, G.M.O., Packman, J.C., Parkin, A., Quinn, P.F., Rose, S.C., Shepher, M., Tellier., S. 2004. Review of Impacts of Rural Land Use and Management on Flood Generation. Report A: Impact Study Report. R&D Technical Report FD2114/TR, Defra, London, UK 152 pp

O'Connell, E., Ewen, J., O'Donnell, G., Quinn, P., 2007. Is there a link between agricultural land-use management and flooding? Hydrol. Earth Syst. Sci. 11, 96–107.

Oldeman, R., Hakkeling, R.T.A., Sombroek, W., 1991. World Map on the Status of Human-Induced Soil Degradation. An Explanatory Note. Global Assessment of Soil Degradation. GLASOD. ISRIC - Winand Centre - ISSS - FAO - ITC, Wageningen.

Orr, H.G., Carling, P.A., 2006. Hydro-climatic and land use changes in the River Lune catchment, NW England: Implications for catchment amangement. River Res. and Appl. 22, 239–325.

Owens, L.B., Edwards, W.M., Van Keuren, R.W., 1997. Runoff and sediment losses resulting from winter feeding on pastures. J. Soil Water Conserv. 52, 194–197.

Pagliai, M., Marsili, A., Servadio, P., Vignzzi, N., Pellegrini, S., 2003. Changes in some physical properties of a clay soil in Central Italy following the passage of rubber tracked and wheeled tractors of medium power. Soil Till. Res. 73, 119–129.

Pattison, I., Lane, S.N., 2011. The link between land-use management and fluvial flood risk: a chaotic conception. Prog. Phys. Geogr. 36 (1), 72–92.

Peña, L.E., Barrios, M., Francés, F., 2016. Flood quantiles scaling with upper soil hydraulic properties for different land uses at catchment scale. J. Hydrol. 541, 1258–1272.

Peng, X.H., Horn, R., 2008. Time-dependent, anisotropic pore structure and soil strength in a 10-year period after intensive tractor wheeling under conservation and conventional tillage. J. Plant Nutr. Soil Sci. 171, 936–944.

Pickett, S.T.A., Cadenasso, M.L., 2009. Altered resources, disturbance, and heterogeneity: a framework for comparing urban and non-urban soils. Urban Ecosyst. 12, 23–44. https://doi.org/10.1007/s11252-008-0047-x.

Pouyat, R.V., Yesilonis, I.D., Russell-Anelli, J., Neerchal, N.K., 2007. Soil chemical and physical properties that differentiate urban land-use type and cover types. Soil Sci. Soc. Am. J. 71 (3), 1010–1019.

Prosdocimi, M., Calligaro, S., Sofia, G., Dalla Fontana, G., Tarolli, P., 2015. Bank rosion in agricultural drainage networks: new challenges from structure-from-motion photogrammetry for post-event analysis. Earth Surf. Processes Landform 40 (14), 1891–1906. https://doi.org/10.1002/esp.3767.

Rogger, M., Alaoui, A., Bloeschl, G., et al., 2017. Land-use change impacts on floods – Challenges and opportunities for future research. Water Resour. Res. 53. https://doi.org/10.1002/ 2017WR020723.

Roy, S., Mistri, B., 2013. Estimation of peak flood discharge for an ungauged river: a case study of the Kunur River, West Bengal. Geography J., 11 https://doi.org/10.1155/2013/214140.

Ryan, C.M., Berry, N.J., Joshi, N., 2014. Quantifying the causes of deforestation and degradation and creating transparent REDD+ baselines: A method and case study from central Mozambique. Appl. Geogr. 53, 45–54.

Salazar, S., Francés, F., Komma, J., Blume, T., Francke, T., Bronstert, A., Blöschl, G., 2012. A comparative analysis of the effectiveness of flood management measures based on the concept of "retaining water in the landscape" in different European hydro-climatic regions. Nat. Hazards Earth Syst. Sci. 12, 3287–3306. https://doi.org/10.5194/nhess-12-3287-2012.

Samson, B.K., Hasan, M., Wade, L.J., 2002. Penetration of hardpans by rice lines in the rainfed lowlands. Field Crops Res 76, 175–188.

Sanyal, J., Densmore, A.L., Carbonneau, P., 2014. Analysing the effect of land-use/cover changes a sub-catchment levels on downstream flood peaks: a semi-distributed modelling approach with sparse data. Catena 118, 28–40.

Scanlon, Bridget R. et al., 2007. Global impacts of conversions from natural to agricultural ecosystems on water resources: Quantity versus quality. Water Resour. Res. 43, 3.

Scherrer, S., Naef, F., Fach, A.O., Cordery, I., 2007. Formation of runoff at the hillslope scale during intense precipitation. Hydrol. Earth Syst. Sci. 11, 907–922.

Schilling, K.E., Gassman, P.W., Kling, C.L., Campbell, T., Jha, M.K., Wolter, C.F., Arnold, J.G., 2014a. The potential for agricultural land use change to reduce flood risk in a large watershed. Hydrol. Process. 28, 3314–3325. https://doi.org/10.1002/hyp.9865.

Schwarz, O., 1986. Zum Abflussverhalten von Waldböden bei künstlicher Beregnung [Runoff characteristics of forest soils as affected by artificial irrigation]. In: Einsele, G. (Ed.), DFG–Research Report on the landscape ecological project 'Schönuch'. VCH Publisher, Weinheim, pp. 161–179.

Schäffer, B., Schulin, R., Boivin, P., 2008. Changes in shrinkage of restored soil caused by compaction beneath heavy agricultural machinery. Eur J Soil Sci 59, 771–783.

Schilling, O.S., Doherty, J., Kinzelbach, W., Wang, H., Yang, P.N., Brunner, P., 2014b. . Using tree ring data as a proxy for transpiration to reduce predictive uncertainty of a model simulating groundwater–surface water–vegetation interactions,. J. Hydrol. 519 (Part B), 2258–2271. https://doi.org/10.1016/j.jhydrol.2014.08.063.

Shoulders, E., Terry, T.A., 1978. Dealing with site disturbances from harvesting and site preparation in the lower coastal plain. In: Proceedings of the Symposium on Principles of Maintaining Productivity on Prepared Sites. Mississippi State University, USA, pp. 85–97.

Seyfried, M.S., Wilcox, B.P., 1995. Scale and the nature of spatial variability: field examples having implications for hydrologic modeling. Water Resour. Res. 31 (1), 173–184. https://doi.org/10.1029/94WR02025.

Silva, S., Barros, N., Costa, L., Leite, F., 2008. Soil compaction and eucalyptus growth in response to forwarder traffic intensity and load. Rev Bras Cienc Solo 32, 921–932.

Singh, J., Hadda, M.S., 2014. Soil and plant response to subsoil compaction and slope steepness under semi-arid irrigated condition. Int. J. Food, Agric. Veter. Sci. 4 (3), 95–104. ISSN 2277-209X.

Smith, C., Johnston, M., Lorentz, S., 1997. Assessing the compaction susceptibility of South African forestry soils. I. The effect of soil type, water content and applied pressure on uni-axial compaction. Soil Till Res 41, 53–73.

Soane, B.D., 1990. The role of organic matter in soil compactibility: A review of some practical aspects. Soil Tillage Res. 16, 179–201.

Soane, B.D., Van Ouwerkerk, C., 1994. Soil compaciton problems in world agriculture. In: Soane, B.D., Van Ouwerkerk, C. (Eds.), Soil compaction in crop production. Elsevier Science & Technology, Amsterdam, pp. 1–21.

Söhne, W., 1958. Fundamentals of pressure distribution and soil compaction under tractor tires. Agricultural engineering, May.

Tóth, B., Makó, A., Tóth, G., Farkas, C., Rajkai, K., 2013. Comparison of pedotransfer functions to estimate the van Genuchten parameters from soil survey information. Agrokémia és Talajtan 62, 5–22.

Troldborg, M., Aalders, I., Towers, W., Hallett, P.D., McKenzie, B.M., Bengough, A.G., Lilly, A., Ball, B.C., Hough, R.L., 2013. Application of Bayesian Belief Networks to quantify and map areas at risk to soil threats: Using soil compaction as an example. Soil Tillage Res. 132, 56–68.

Van den Akker, J.J.H., 2004. SOCOMO: a soil compaction model to calculate soil stresses and the subsoil carrying capacity. Soil Tillage Res. 79, 113–1227.

Van den Akker, J.J.H., 1988. Model computations of subsoil stress distribution and compaction due to field traffic. In: Proceedings of the 11th International Conference of ISTRO, Edinburth, UK, pp. 403–408.

Van den Akker, J.J.H., 1994. Prevention of subsoil compaction by tuning the wheel load tot he bearing capacity of the subsoil. In: Proceedings of the 13th International Conference of ISTRO, Aalborg, Denmark, pp. 537–542.

Villarini, G., Strong, A., 2014. Roles of climate and agricultural practices in discharge changes in an agricultural watershed in Iowa. Agric. Ecosyst. Environ. 188, 204–211. https://doi.org/10.1016/j.agee.2014.02.036.

Viglione, A., Merz, B., Viet Dung, N., Parajka, J., Nester, T., Blöschl, G., 2016. Attribution of regional flood changes based on scaling fingerprints. Water Resour. Res. 52, 5322–5340. https://doi.org/10.1002/2016WR019036.

Vzzotto, V.R., Marchezan, E., Segabinazzi, T., 2000. Effects of cattle trampling on lowland soil physical properties. Ciencia Rural. 30, 965–969.

Warburton, M.L., Schulze, R.E., Jewitt, G.P.W., 2012. Hydrological impacts of land use change in three diverse South African catchments. J. Hydrol. 414–415, 118–135.

Wang, P., Hu, Z., Zhao, Y., Li, X., 2016. Experimental study of soil compaction effects on GPR signals. J. Appl. Geophys. 126, 128–137.

Weiler, M., McDonnell, J.J., 2007. Conceptualizing lateral preferential flow and flow networks and simulating the effects on gauged and ungauged hillslopes. Water Resour. Res. 43, W03403. https://doi.org/10.1029/2006WR004867.

Western, A.W., Blöschl, G., Grayson, R.B., 1998. How well do indicator variograms capture the spatial connectivity of soil moisture? Hydrol. Process. 12, 1851–1868.

White, M.D., Greer, K.A., 2006. The effects of watershed urbanization on the stream hydrology and riparian vegetation of Los Penasquitos Creek. California Landsc. Urban Plann. 74, 125–138.

Wösten, J.H.M., Lilly, A., Nemes, A., Le Bas, C., 1999. Development and use of a database of hydraulic properties of European soils. Geoderma 90, 169–185.

Wright, S.F., Starr, J.L., Paltineanu, I.C., 1999. Changes in aggregate stability and concentration of glomalin during tillage management transition. Soil Sci. Soc. Am. J. 63, 1825–1829.

Yan, D., Schneider, U.A., Schmid, E., Huang, H., Pan, L., Dilly, O., 2013. Interactions between land use change, regional development, and climate change in the Poyang Lake district from 1985 to 2035. Agric. Syst. 119, 10–21.

Young, R.N., Warkentin, B.P., 1966. Introduction to Soil Behavior. The Macmillan Co., New York, p. 451.

Yung, K.Y., Kitchen, N.R., Sudduth, K.A., Lee, K.S., Chung, S.O., 2010. Soil compaction varies by crop management system over a claypan soil landscape. Soil Tillage Res. 107, 1–10.

Zehe, E., Blöschl, G., 2004. Predictability of hydrologic response at the plot and catchment scales: role of initial conditions. Water Resour. Res. 40, W10202. 10·1029/2003WR002869.

Zhao, Y., Peth, S., Horn, R., Krümmelbein, J., Ketzer, B., Gao, Y., Doerner, J., Bernhofer, C., Peng, X., 2010. Modeling grazing effects on coupled water and heat fluxes in Inner Mongolia grassland. Soil Till. Res. 109, 75–86.

Zimmermann, B., Elsenbeer, H., De Moraes, J.M., 2006. The influence of land-use changes on soil hydraulic properties: Implications for runoff generation. Forest Ecol. Manage. 222 (1–3), 29–38. https://doi.org/10.1016/j.foreco.2005.10.070.