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Stormwater Soakage Wells Do Not Affect Vertical Ground Movement in a Roadside Tree Site with Reactive Clay Soil

By G.M. Moore, T. Johnson, and C. Brien

Abstract. Background: Sustainable cities will require water sensitive urban design (WSUD) that integrates street trees, urban soils, and engineered infrastructure. However, there can be a perception that these systems contribute to ground/soil movement that can be problematic for hard infrastructure. There is concern that diverting water into kerbside harvesting systems for street trees may exacerbate ground movement. Method: Twenty-eight small kerbside stormwater harvesting systems that diverted storm runoff into roadside soakage wells were dispersed along a residential street in an inner suburb of the City of Adelaide, South Australia. The wells can be utilized with or without the presence of street trees, but greater utility and environmental benefits could be achieved with vegetation. Regular measurements of ground level were undertaken to determine ground movement over a period of 2 years, comparing sites with and without soakage wells. Results: Results showed that stormwater harvesting and infiltration into the site's reactive clay did not increase ground movement at the kerb or at the road surface during periods of above and below average rainfall. Kerb levels generally remained within +10 mm (heave) and −15 mm (settlement) of the reference datum, and movement at the top of the asphalt road seal was no greater than +7 mm or −6 mm. The maximum extent of ground movement (sum of the maximum heave and maximum settlement) at any point was 26 mm, but typical movement at 9 points, 6 of which were near inlets, was 4 mm. Ground movement was of similar amplitude near and further from infiltration points and was unaffected by stormwater harvesting. Conclusion: The use of trees within WSUD, particularly in fine clay soils in which root growth increases water harvesting and storage, can substantially contribute to urban hydrology through canopy rainfall interception, hydraulic redistribution, enhanced soil conductance through biopore creation, and preferential flow along root channels. This research shows that the presence of soakage wells does not lead to increased ground movement in reactive clay soils.

Keywords. Green Infrastructure; Reactive Clay Soils; Soakage Wells; Stormwater; Stormwater Management.

INTRODUCTION

Water is as fundamental to life in cities as it is in natural environments. Massive financial investment services this large component of urban infrastructure (Kennedy et al. 2007), but climate change related weather extremes (Stocker 2013; Blunden and Arndt 2016) are straining the capacity of traditional approaches to manage stormwater runoff, flooding, and water supply (Sharma et al. 2016; Miller and Hutchins 2017; Jegatheesan et al. 2019). Unprecedented urban growth (United Nations Population Division 2018) compounds these water related issues and increases demands upon and diminishes provision of ecosystem reliant urban water supplies. Predicted global population growth to 8.5 billion by 2030, with 60% living in cities (United Nations Population Division 2018), will continue to drive development, challenge urban water managers, and potentially further diminish ecosystem services, such as tree canopy cover, urban cooling, and green infrastructure.

Conventional drainage and sealed urban surfaces of the past effectively separated stormwater from soils and urban vegetation. The restricted movement of water and gases through the soil-plant-atmosphere continuum led to increased stormwater discharge and flooding (Rosenberger et al. 2021; Wang et al. 2021) and more frequent and prolonged water stress in urban vegetation (Thom et al. 2020; Rötzer et al. 2021). Globally, water sensitive urban design (WSUD), sponge cities, low impact developments, and sustainable

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drainage systems (Fletcher et al. 2015; Leng et al. 2020) are ways communities are moving toward water sensitive, greener, sustainable cities (Dada et al. 2021; Fogarty et al. 2021). By managing stormwater *in-situ*, WSUD provides additional water and nutrients to sustain urban trees and other vegetation (Denman et al. 2016; Grey et al. 2018a; Tirpak et al. 2019). Some of the common, major stormwater pollutants and their typical concentrations found in stormwater include forms of nitrogen such as NO_3 (2 mg L^{-1}), organic nitrogen (4 mg L^{-1}), phosphate (0.6 mg L^{-1}) and trace levels of copper, sodium, and magnesium chloride (Denman et al. 2016). WSUD can help mitigate urban heat island effects (Wang et al. 2019; Bartesaghi-Koc et al. 2020), reduce the pollution of receiving waters (Beecham et al. 2012), and reduce demands on potable water supplies while mitigating flood risk (Argue 2004; Revelli and Porporato 2018).

Green Infrastructure

Greening WSUD infrastructure with trees and other plants can be highly valuable; vegetation benefits from water while simultaneously decreasing the load on the WSUD device and improving its storm water management capacity and performance (Day and Dickinson 2008). Vegetation is known to enhance infiltration, even in compacted urban soils (Bramley et al. 2003; Scanlan and Hinz 2010; Chandler et al. 2018), by up to 21 times (Xie et al. 2020). In a laboratory experiment, plant roots increased hydraulic conductance through compacted soil by 27 times (Bartens et al. 2008). Vegetation type, plant age, and soil type affect the magnitude of the benefits to infiltration (Shi et al. 2021).

Green infrastructure is increasingly being used to restore more natural hydrology in urban areas (Berland et al. 2017; Thom et al. 2020), to strengthen community engagement with nature (Matthews 2020; Parker and Simpson 2020), and to enhance ecosystem service delivery (Elmqvist et al. 2015; Livesley et al. 2016). Bioretention systems such as swales and basins can incorporate vegetation into their design, in addition to filter media, for biodiversity conservation and aesthetic purposes and to purify water prior for downstream discharge or for infiltration (Bjørn and Howe 2023; Bonciarelli et al. 2025). Although they can be highly beneficial, planted treatments require space at ground level which is highly contested in cities. Subsurface soakage systems such as infiltration trenches, galleries, pits, and drywells (Maliva 2020) can deliver water to deep rooted vegetation such as street and park trees while occupying negligible surface area, thus supporting alternative urban land uses. Their longevity, large leaf area, and relatively small footprint on the land surface make trees more suitable for delivering natural hydrologic services in many urban areas than smaller, shorter lived plants. With leaf areas of 2 to 4 times their canopy area (Baptista et al. 2018), trees are better able to utilize the locally abundant soil moisture delivered by subsurface WSUD systems and to increase human and environmental benefits through enhanced evapotranspiration (Coutts et al. 2013; Jegatheesan et al. 2019; Bikomeye et al. 2021; Brears 2023), particularly in arid and semi-arid areas where high vapour pressure deficits across leaf surfaces drive greater transpiration (Vico et al. 2014; Wang et al. 2019).

To access the water they need to thrive, trees must establish an adequate root-soil interface (Moore 2001; Day et al. 2010; Watson et al. 2014). This requires a sufficiently large volume of soil (Kopinga 1991; Lindsey and Bassuk 1992; Leake and Haege 2016) which must be exposed to receive rainfall and to allow gaseous diffusion. Infiltration trenches, leaky wells, soakage wells, pervious paving, and other WSUD devices support these exchanges more effectively than many turfed urban green spaces (McGrane 2016); the hydrologic performance of these devices can exceed infiltration through lawn by a factor of 10 (Newcomer et al. 2014).

The capacity of trees to substantially benefit urban stormwater management and WSUD is based on soil-plant-atmosphere interactions and synergies between trees and microbiome ecosystems (Baldrian 2017). Tree canopies detain 20% to 44% of incident rain during low to moderate intensity and moderate duration storm events (Livesley et al. 2014; Nytch et al. 2019), greatly reducing surface and stream discharges as well as helping to improve stormwater quality (Xiao et al. 1998; Denman et al. 2016). Canopy interception can generate stemflow (Carlyle-Moses et al. 2018; Van Stan and Allen 2020), which delivers water to the soil in urban tree pits from where it can be infiltrated along root-induced preferential flow paths (Johnson and Lehmann 2006; Di Prima et al. 2020; Gonzalez-Ollauri et al. 2020). Many small flow paths are created through fine root turnover and the natural seasonal replacement of short lived small roots (Lukac 2012). Interconnected biopores created through fine root turnover increase hydraulic conductance,

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water storage capacity, and aeration of soils, and support microbiome species diversity and abundance.

Hydraulic redistribution (HR) of water through trees from zones of higher potential to zones of lower potential is not uncommon in ecohydrology (Burgess et al. 1998; Caldwell et al. 1998; Eamus et al. 2006; Neumann and Cardon 2012), but there has been little research of HR in urban trees. HR can move water between soils of different depths (Caldwell and Richards 1989), from one part of a root zone to another (Nadezhdina et al. 2009; Liu et al. 2021) and to root zones of adjacent trees (Hafner et al. 2017). Bidirectional flow in stems and roots is fundamental to HR across dynamic water potential gradients existing between the many interfaces of trees and their environs. Synchronous bidirectional sap flow in daytime countercurrent flows in different radial sectors of roots supply water to leaves for transpiration while simultaneously transporting water to zones of low potential in the soil (Nadezhdina et al. 2009; Liu et al. 2021). Hydraulic redistribution of harvested fog moves water from the atmosphere into leaves, stems, and roots and potentially into soil (Eller et al. 2013). Mycorrhizae have been implicated in HR, aiding water movement between trees and soil (Pickles and Simard 2017; Penuelas and Sardans 2021).

HR functions better in finely textured clay soil (Shi et al. 2021), which exerts higher matric suction and supports steeper water potential gradients than coarser soils, but the application of WSUD devices on clay remains limited in Australia. Low application of infiltration-based WSUD approaches on clay may be due to perceptions of poor performance on soils of low hydraulic conductivity and the potential for water-related ground movement. Infiltration has been shown to effectively manage stormwater on low permeability clays (Dreelin et al. 2006; Fassman and Blackbourn 2010), and the mechanisms of infiltration enhancement and water distribution suggest that perceptions of low hydraulic conductance should not discourage the use of WSUD on clay when combined with trees and other elements of green infrastructure.

Soil Water-Related Ground Movement

Concerns with infiltration into reactive clay arise from the perceived risk of damage to buildings or infrastructure due to moisture-related ground movement, an effect which is sometimes associated with soil desiccation due to enhanced extraction of water by trees (Biddle 1983; Cameron et al. 2006; Sun et al. 2022). This research examined whether soakage wells on a typical urban street without trees growing in them affected ground movement. The effect of water infiltration into the medium of the wells on surrounding site soils was monitored without the compounding influence of water uptake by street trees. The extent of soil shrinkage or swelling due to changes in water content relates to soil composition, the primary factors being mineralogy and clay content (Ross 1978; Boivin et al. 2004). In this experimental site, the soil was highly reactive Adelaide clay, so if water infiltration into the soakage wells was going to contribute to ground movement, it would be revealed over the period of data collection. Differential soil movement beneath built structures due to change in water content can result in stresses which lead to property damage (Day 1991). Such movement has been described as "…the most damaging geohazard in Britain…" and was implicated in damage valued at £3 billion while similar damage in the USA cost $15 billion USD per year (Jones and Jefferson 2012).

No literature was identified which reported problematic ground movement in relation to infiltration associated with WSUD. However, reduced ground movement near trees was reported in response to infiltration through permeable paving, as was increased movement beyond the influence of trees, but the differences were inconsequential in comparison with annual ground movement (Johnson et al. 2020). Research into the use of soakage wells to increase water infiltration to soil was recommended by Goldfinch (1995) to investigate its potential for offsetting the impacts on house foundations of water extraction by trees.

Dispersed Stormwater Infiltration to Reduce Risk

To maximise its contribution to urban water management and provision of other community and environmental benefits, green infrastructure must be distributed widely throughout urban areas, including on reactive soils which are widespread in some Australian cities. A cautious approach suggests the use of many dispersed infiltration devices in combination with trees, to benefit both stormwater (flooding) management and harvesting efficiency (Ebrahimian et al. 2019; Liang et al. 2020; Shahzad et al. 2021; Shahzad et al. 2022a; Shahzad et al. 2022b) and to provide passive irrigation for urban vegetation with minimum risk. Use of dispersed infiltration devices would reduce the risk of plant water stress which may be associated

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with larger WSUD devices in climates dominated by rain events of low intensity and short duration (Tu et al. 2020) and the likelihood of waterlogging which has been shown to be potentially problematic to tree growth in WSUD devices in low conductance soils (Grey et al. 2018b).

Kerbside stormwater harvesting devices designed to deliver runoff from road surfaces for infiltration in tree root zones at depth sufficient to avoid evaporation loss from the soil surface have been shown to benefit tree growth in semi-arid climates (Luketich et al. 2019). The use of dispersed infiltration devices in combination with street trees remains a novel WSUD approach in Australian cities; it aims to restore more natural hydrology and to deliver passive irrigation at depth to street trees (Sapdhare et al. 2018). Such devices operating in residential streets harvested approximately 1.6 kL of water per device in one year (Shahzad et al. 2022a). Kerbside stormwater harvesting remains limited in application however, possibly due to the knowledge gap surrounding point source infiltration into reactive soils and the potential for soil movement affecting infrastructure. This research was an attempt to close this knowledge gap in relation to soakage wells so that their wider use in WSUD might be encouraged. This could foster a greater interest in planting street trees that would be healthier with greater canopy cover, as they accessed greater quantities of water via the soakage wells. Such trees could then contribute greater shade and cooling as climate change takes effect on the City of Adelaide.

Experimental Hypothesis

This experiment was designed to measure ground movement at sites equipped with kerbside stormwater harvesting and infiltration devices. The experiment tested the hypothesis that stormwater infiltration into reactive soil in the road verge increased ground movement. To test this hypothesis, vertical ground movement was measured where stormwater was infiltrated into road verges (nature strips/tree lawns) in a residential street.

MATERIALS AND METHODS

Experimental Design and Site Conditions

Twenty-eight stormwater harvesting inlets were installed in 2014 in Eynesbury Avenue in Hawthorn (−34.972543, 138.612617), a long-established inner suburb approximately 4 km south of Adelaide, the capital city of South Australia. The infrastructure was built as a working demonstration in a residential street. The stormwater harvesting device used was the TREENET Inlet (Space Down Under, St. Marys, South Australia, Australia), which consisted of a slotted inlet device cast into the concrete kerb next to a shallow dish formed in the concrete gutter (Figure 1). A slot in the device's faceplate was aligned above the centre of the gutter dish and was positioned below adjacent gutter levels to receive stormwater inflow. Concrete kerbing had a 150-mm tall upright face adjacent to a 300-mm wide gutter which abutted the road edge. Gutters conveyed stormwater runoff from the impervious road surface, footpaths (sidewalks), verges, and from adjacent private properties.

The 8-m wide road was typical of residential streets in the locality, consisting of an asphaltic concrete seal over compacted rubble above a compacted subgrade of silty clay soil. Inlets were distributed along 290 m of the road with 15 on the north and 13 on the south side. The mean separation between of the inlets was 16.9 m (SD 3.9 m). The variable separation between inlets was necessary due to the location of pre-existing infrastructure, utilities, and street trees.

The longitudinal gradient of the road varied between 1.2% and 1.4%. Inlets harvested approximately 14 L/m from gutter flows of 30 L/m at such gradients, and harvest volume increased as gutter flow increased (Shahzad et al. 2022b). The total impervious catchment area of the 28 inlets was 1.2 ha (Sapdhare et al. 2019). The low intensity of Adelaide's

Figure 1. Kerbside inlet installation and access cover above soakage well.

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540-mm average annual precipitation, with 80% falling at 4 mm/hr or less (Pavelic et al. 1992), meant that inlets harvested most of the gutter flows during most rain events.

Operating under field conditions, the inlets' design generally prevented ingress of sediment which might have reduced inflow capacity, but leaf litter did build up and partially clog inlets at times. Routine (monthly) road sweeping maintained inlet function, and residents also manually cleared some inlets of litter. When gutter flow exceeded inlet harvest or detention capacity during intense events, the surplus bypassed and flowed to downstream inlets or beyond and into the conventional pit and pipe stormwater drainage network.

Harvested stormwater flowed from the inlet's dish in the gutter, through the slot in the faceplate, and through a PVC pipe into a soakage well in the adjacent verge. Soakage wells were cylindrical, 0.45 m in diameter, 1.00 m deep below the top of the kerb and centred 0.60 m behind the back of the kerb. A 225-mm diameter slotted pipe in the centre of the well distributed the harvested stormwater into a filter medium 110-mm thick which surrounded the pipe (Figure 2), through which the harvested water soaked into surrounding soil. Geotextile fabric was not used to separate the filter medium from the surrounding site soil.

The detention capacity of the soakage wells varied between 50 L and 70 L due to the porosity of 4 different filter media used for a concurrent experiment (Sapdhare et al. 2018; Sapdhare et al. 2019). Porosity of the different media ranged between 25% (sandy loam) and 40% (16-mm gravel). The exfiltration rates

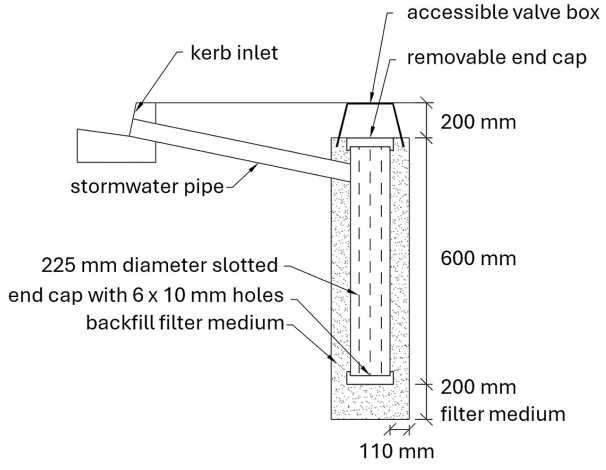

Figure 2. Kerbside inlet and soakage well section view.

of wells with different filter media varied from a maximum of 72 ± 9 L/h for wells with gravel backfill to 58 ± 12 L/h for wells backfilled with water treatment solids, a proprietary material comprised largely of granulated clay residue from water filtration (SPACE, Space Down Under, Urrbrae, South Australia, Australia); 20 ± 1 L/h for site clay returned as backfill following well construction; and a minimum of 17 ± 1 L/h for wells with sandy loam backfill. The SPACE medium has self-mulching properties, so particle size varies through wetting and drying cycles (Sapdhare et al. 2019).

The experimental site was located on an alluvial fan approximately 600-m north of Brown Hill Creek and 2-km west of the lower slopes of the Mount Lofty Ranges. Shrink/swell indices (Standards Australia 2003; Fityus et al. 2005) in an adjoining street varied between 0.1% and 4.2% strain per unit change in total soil suction (log_{10}kPa)(Johnson et al. 2020), which informed the classification of sites in the vicinity to be of low to moderate reactivity (Standards Australia 2011). Soils are reported as red-brown earths (RB3, RB5)(Sheard and Bowman 1996).

Monitoring Ground Movement

Ground movement was measured at survey points established at the top of the kerb directly above each inlet (inlet kerb), offset 3 m either side of each inlet (offset east; offset west), and at the midpoint between inlets (midpoint kerb). Surveys were conducted by licensed surveyors using a Leica DNA 03 precise digital level (Leica Geosystems AG, Heerbrugg, Switzerland) and a fiberglass staff. Over the range of these surveys, its accuracy was 0.33 mm.

Separation between inlets and midpoints was 8.4 ± 4.0 m. Vertical movement was also measured at survey points on the asphalt road surface 2 m from the kerb face near each inlet (inlet road) and midpoint (midpoint road) to reveal ground movement beneath the road seal. Midpoints (midpoint kerb and midpoint road) served as controls. The midpoint was midway between the soakage wells so that kerb level changes near the soakage wells were compared with kerb level changes midway between the soakage wells (the furthest point from the point of infiltration and least affected by infiltration). Similarly with surveys done on the road surface 2 m from the kerb, level changes near the soakage wells were compared with the level changes midway between the soakage wells.

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Surveys were conducted on 7 dates between and including 2014 October 23 and 2016 July 20. Survey dates were selected to measure the greatest extent of soil expansion which typically followed Adelaide's winter rainfall (June to August) and the greatest soil shrinkage following the end of summer (surveyed during early autumn, March to early April). The dates correspond to the Australian autumn, winter, spring, summer, autumn, and winter, respectively. The surveyors reported vertical ground movement to within 1 mm relative to a benchmark installed nearby. Moisture related movement of the steel rod benchmark was assumed to be negligible, as the rod was sleeved in a steel pipe through the top 4.5 m of the soil profile (Johnson et al. 2020). The elevation recorded at each point during the initial survey on 2014 October 23 was used as the datum for that point (0.000 m); the amplitude of subsequent vertical movement was analysed. Rainfall data were obtained from the Government of Australia's weather station at Brown Hill Creek, 1.2 km to the southeast of the experimental site (Australian Government 2021).

Statistical Analysis

Analysis of the vertical ground movement data involved fitting a linear mixed model in the R statistical computing environment (R Foundation, Vienna, Austria) using the ASReml (Butler et al. 2023) and asremlPlus (Brien 2021) software packages. The linear mixed model used was:

$$E[Y] = \text{Type.point} + \text{Type.point:Substratum} + \text{Street.side} + \text{Type.point:Street.side:} + \text{Type.point:Substratum:Street.side} + \text{Day} + \text{Type.point:Day} + \text{Type.point:Substratum:Day} + \text{Street.side:Day} + \text{Type.point:Street.side:Day} + \text{Type.point:Substratum:Street.side:Day} \quad (1)$$

$$Var[Y] = \text{Point} + \text{idh (Type.point:Day):Point} \quad (2)$$

where Y is the random variable for a response from the data, E[Y] is the expectation model that consists of a set of fixed terms that could affect the mean value of Y, and Var[Y] is the variance model that consists of random terms that capture the variation in Y. The fixed terms are: (1) Type.point that allows for consistent differences between the different types of survey point (kerb inlet, kerb offset east, kerb offset west, kerb midpoint, road inlet, road midpoint); (2) Type.point:Substratum that reflects differences between the different substratum materials used for the kerb inlets; (3) Street.side that represents a consistent difference between the side of the street on which the measurement was made (north or south); (4) Type.point:Street.side that allows Type.point differences to vary with Street:Side; (5) Type.point:Substratum:Street.side that allows Substratum differences to vary with the Street:Side; (6) Day that takes into account consistent differences between the days of observation; and (7) Type.point:Day, Type.point:Substratum:Day, Street.side:Day, Type.point:Street.Side:Day, and Type.point:Substratum:Street.Side:Day that allow Type.point, Type.point:Substratum, Street.side, Type.point:Street.Side, and Type.point:Substratum:Street.Side differences to vary with Day. The random terms are: (1) Point that allows for consistent difference across days between the survey points; and (2) var (Type.point:Day)Point specifies that the variance of individual Points will differ between the combinations of Type.point and Day.

This model was selected using the Akaike Information Criterion (AIC) by comparing the AICs for models with homogeneous variance and with differential variance and selecting the model with the smallest AIC. Similarly, the AICs for models with and without the Point variance term were compared. Wald *F*-tests at a 5% significance level were conducted to assess the significance of the fixed terms. The 4-factor fixed term was tested first. Only if the 4-factor term was nonsignificant were the 3-factor terms tested, and then only those 2-factor terms that were not involved in a significant 3-factor term were tested. Finally, any single factor term not involved in a significant term was tested.

The linear mixed model was based on the two experimental design variables (Type of point and Substratum material), the two variables reflecting the physical site (Sides of the Street and the Points on each Street-side), and the time variable Day (the days of measurement). The fixed terms in the model are all possible combinations of the variables Type of point, Substratum, Street-side and Day, except that Substratum is linked and specific to Type of point. The random terms include random variation between the Points in this experiment and random variation of the physical units on each Day, with plots of the data revealing that the latter variation needed to be allowed to differ between the combinations of Type of point and Day. The fitted model was used to produce 'predicted' or 'adjusted' means for the vertical ground

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movement values for the significant terms. Least significant differences (LSD = 5%) were also calculated from the linear mixed model analysis.

RESULTS

Surveys

Kerb levels generally remained within +10 mm (heave) and −15 mm (settlement) of the datum (Figure 3). Ground movement measured at the top of the asphalt road seal, 2 m from the kerb, was no greater than +7 mm or −6 mm during the experiment (Figure 4). Surveyed levels at the offsets 3 m on either side of the inlets were similar to levels at the nearby inlet. The maximum kerbtop displacement from datum level was at point 8, an inlet site that had settled 19 mm on 2015 March 11. The maximum total extent of ground movement (sum of the maximum heave and maximum settlement over the duration of the experiment) at any survey point was 26 mm (point 8, at the top of the kerb above an inlet). The greatest total movement measured at the kerbtop at a midpoint between inlets was 22 mm (point 135). The smallest total movement recorded at any survey point was 4 mm; this minimal movement occurred at 9 points, 6 of which were near inlets (Table 1).

The broad vertical spread of data points in the western end of the street (left side of Figure 3) and eastern end of the street (right side of Figure 3) indicate greater seasonal movement in these parts of the street than in the centre. As the infiltration devices were dispersed along the street, this result is most likely due to greater soil reactivity (higher shrink/swell index), a greater quantity of reactive soil in the profile in these eastern and western locations, and lower soil reactivity or quantity of reactive soil in the centre.

The greatest kerb heave occurred in early spring 2015 (September 21) at all kerb survey points except point 27, an inlet at which maximum heave occurred in midwinter (2016 July 27). The greatest kerb settlement was on 2015 March 11 at all kerb points except point 148, an inlet at which maximum settlement occurred on 2016 April 12. Maximum heave at road surface survey points was measured on 2015 September 21 or 2015 December 10 at most points, and maximum settlement at most road survey points was measured on 2016 April 12 or 2016 July 20, although heave and settlement maxima were also measured on other dates at some road survey points.

Rainfall

Below average rainfall was recorded over the 16 months from September 2014 to December 2015 inclusive; 500 mm fell compared to the longterm average over these months of 674 mm. Above average rain fell from January 2016 to July 2016 inclusive, with 468 mm received compared to the historical average of 320 mm over these 7 months. Monthly evapotranspiration potential varied from 30 mm per month during winter to 120 mm per month during summer. Mean and actual rainfall and evapotranspiration are plotted in Figure 5.

Linear Mixed Model Analysis

The different substratum media used for the kerb inlets had no effect on the vertical ground movement ($P > 0.05$). There were no significant differences between the road inlet and road midpoint survey points on any dates on both sides of the road. Differences in vertical ground movement between the combinations of the survey point types (inlet kerb, midpoint kerb, offset east, offset west, inlet road, midpoint road), street side (north or south), and survey dates were significant ($P \leq 0.05$).

Except for the south side of the street on 2015 December 10 and 2016 April 12, there were significant

Table 1. Survey point numbers and types at which minimum (4 mm) vertical ground movement was recorded over the duration of the experiment.

	Survey point location			
	Road surface		Kerbtop	
	Inlets	Midpoints	Inlets	Midpoints
Survey point numbers	29; 35; 93; 99	19; 25; 152	121; 160	
Quantity	4	3	2	0

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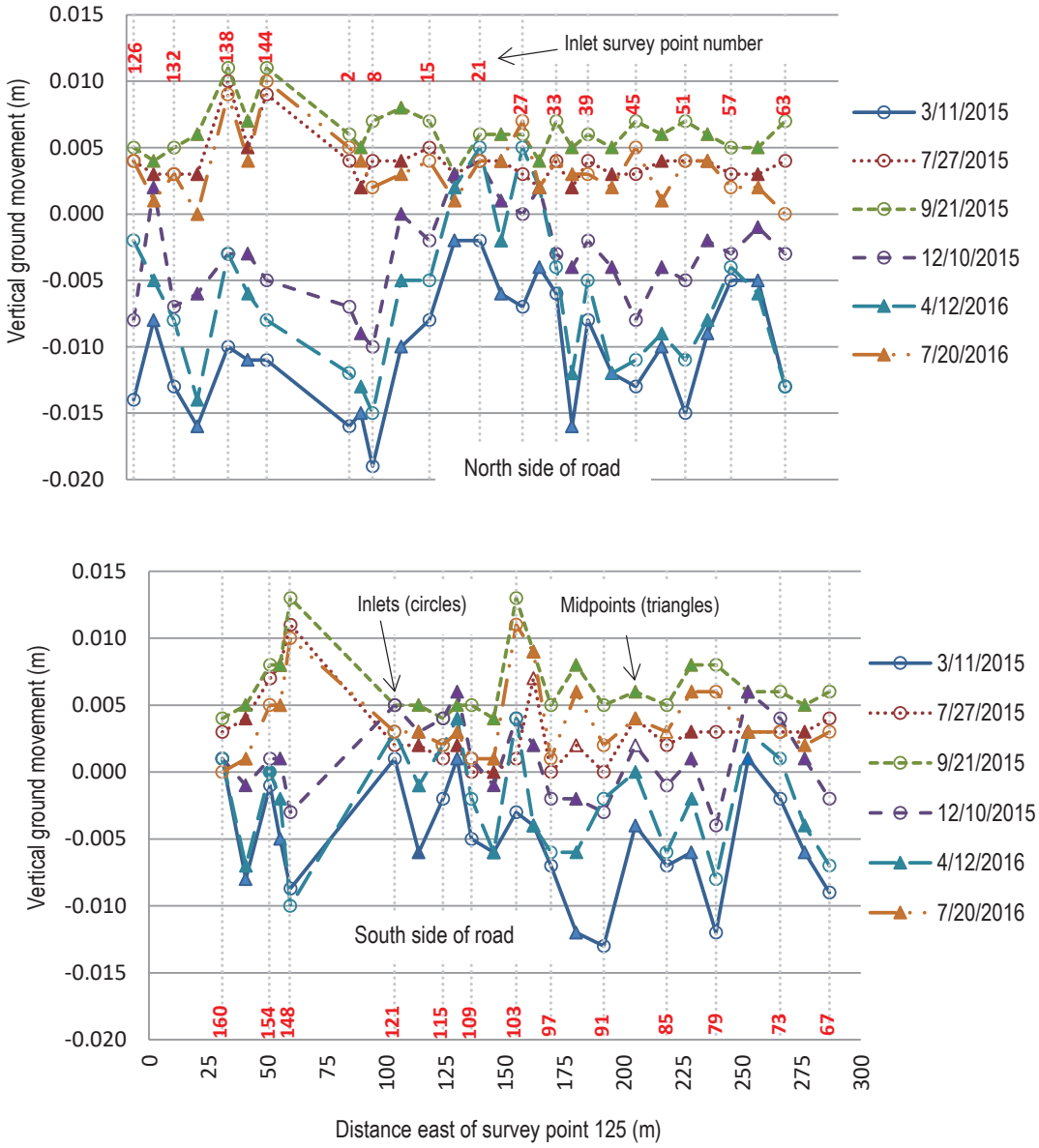

Figure 3. Kerbtop survey levels at inlets (identified by circle markers, vertical lines, and survey point numbers) and at midpoints between inlets (triangle markers) relative to datum survey level (0.000 m) on 2014 October 23. Survey point 125 (a west offset) is the most westerly survey point. Plotting the data points to scale distance east of this point presents the data in the graph in the fashion of a 'Northern elevation view' along the street.

differences between the road survey points and the kerb survey points on all dates and on both sides of the street, and the magnitude of the difference varied between survey dates (Figure 6). The only differences between kerb survey points on any date were between kerb midpoint and kerb offset east on the north side of the road on 2015 September 21 and between the kerb midpoint and the kerb offset east and kerb inlet survey points on the north side of the road on 2016 July 20. There were no differences between kerb survey point types on either the north or south sides of the road on the other 4 survey dates (Figure 6). Ground movement at the kerb survey points was greater than at the road survey points (Figures 6 and 7). During the dry period, on 2015 March 11 and on 2015 December 10, at kerb inlet and at kerb midpoints the north side of the road had settled more than the south side. Greater settlement of the north side than the south also occurred at kerb midpoints on 2016 April 12 but not at kerb inlets.

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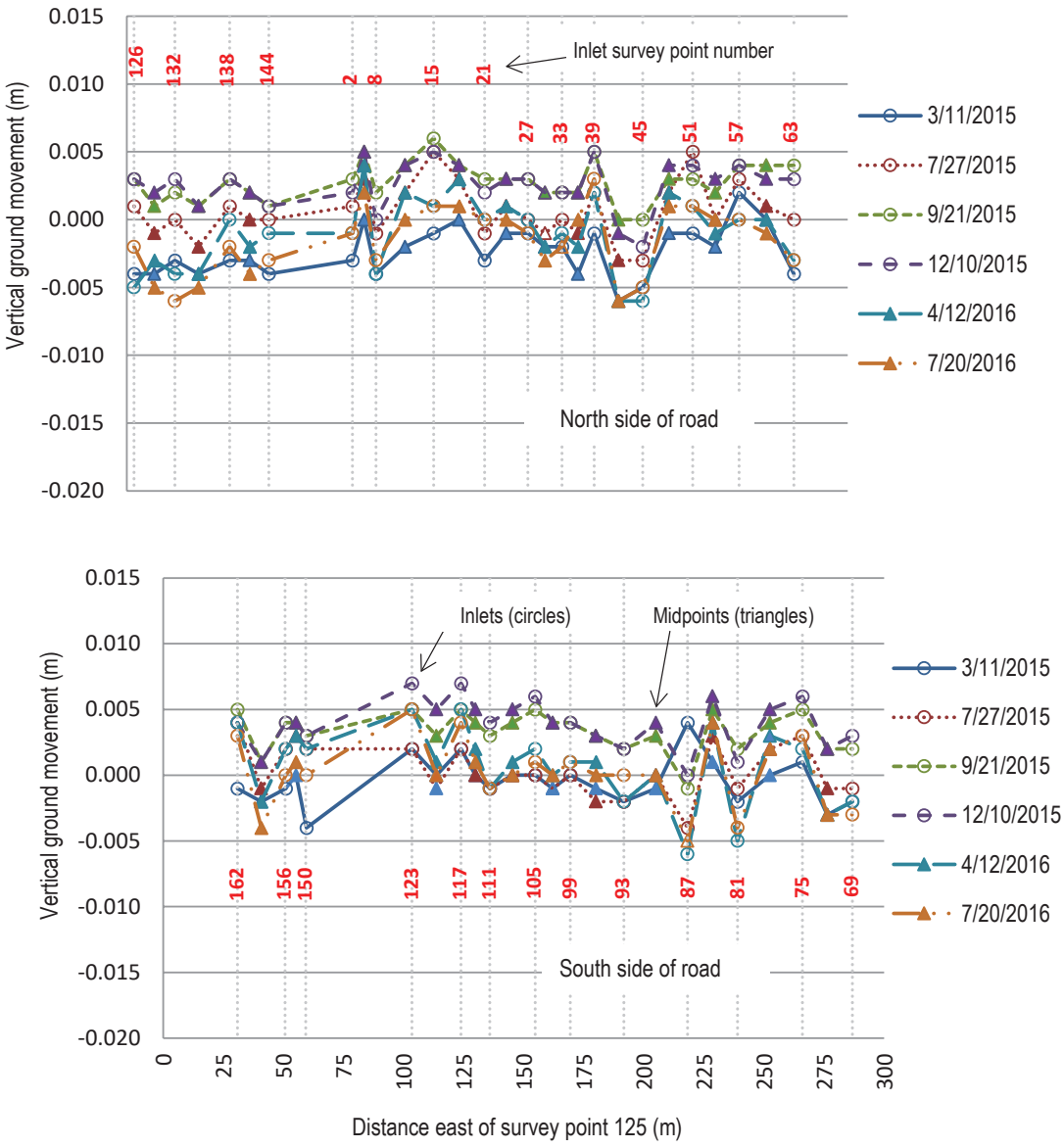

Figure 4. Road surface survey levels 2 m from kerb near inlet (identified by circle markers, vertical lines, and survey point numbers) and midpoint locations (triangle marker) relative to datum survey level (0.000 m) on 2014 October 23.

DISCUSSION

The experiment tested the hypothesis that stormwater infiltration into reactive soil increased ground movement. Results showed the amplitude of ground movement at survey points above stormwater infiltration wells was usually no different to survey points without infiltration. Ground movement was consistent with shrinkage and heave of the low to moderately reactive soils under typical seasonal weather conditions. Stormwater harvest volume would not have exceeded the 1.6 kL per year (averaged per inlet) reported in Shahzad et al. (2022a) due to the smaller soakage wells used in this experiment. Given the ground movement was consistent with normal seasonal movement, limited infiltration volume, and reduced or eliminated effects at the midpoints of water infiltrated at the wells due to separation distance, it is concluded that the similar movement at the inlets and midpoints indicated that ground movement was unaffected by infiltration. Under the conditions of this experiment and contrary to the experimental hypothesis, the infiltration of stormwater into low to

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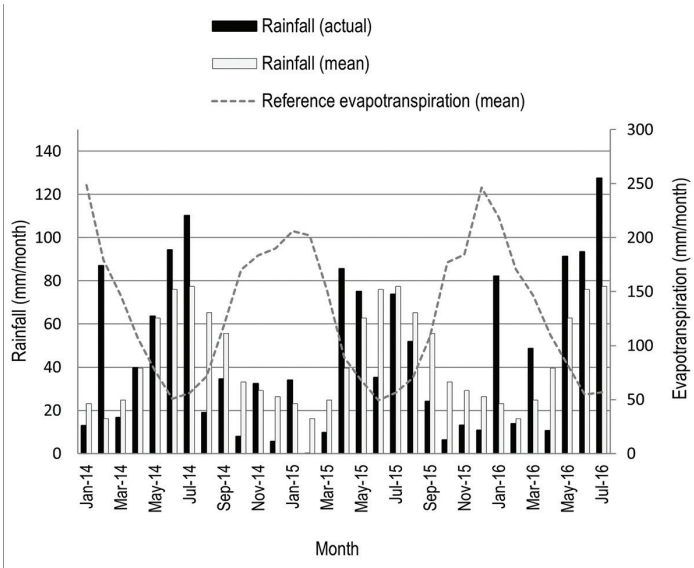

Figure 5. Mean and actual rainfall and potential evapotranspiration data for January 2014 to July 2016.

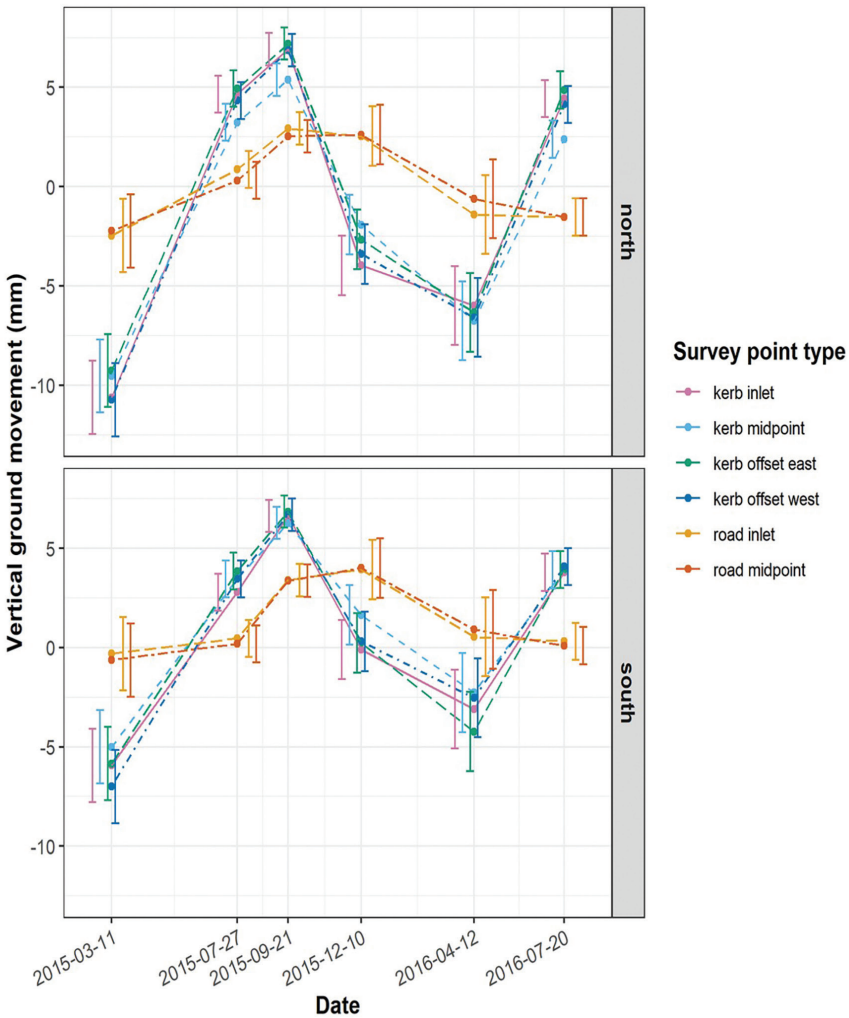

Figure 6. Adjusted mean vertical ground movement at different kerb and road surface survey point types on the north and south sides of the road on different survey dates. Error bars show half of the average LSD (5%); means with error bars that overlap are not significantly different.

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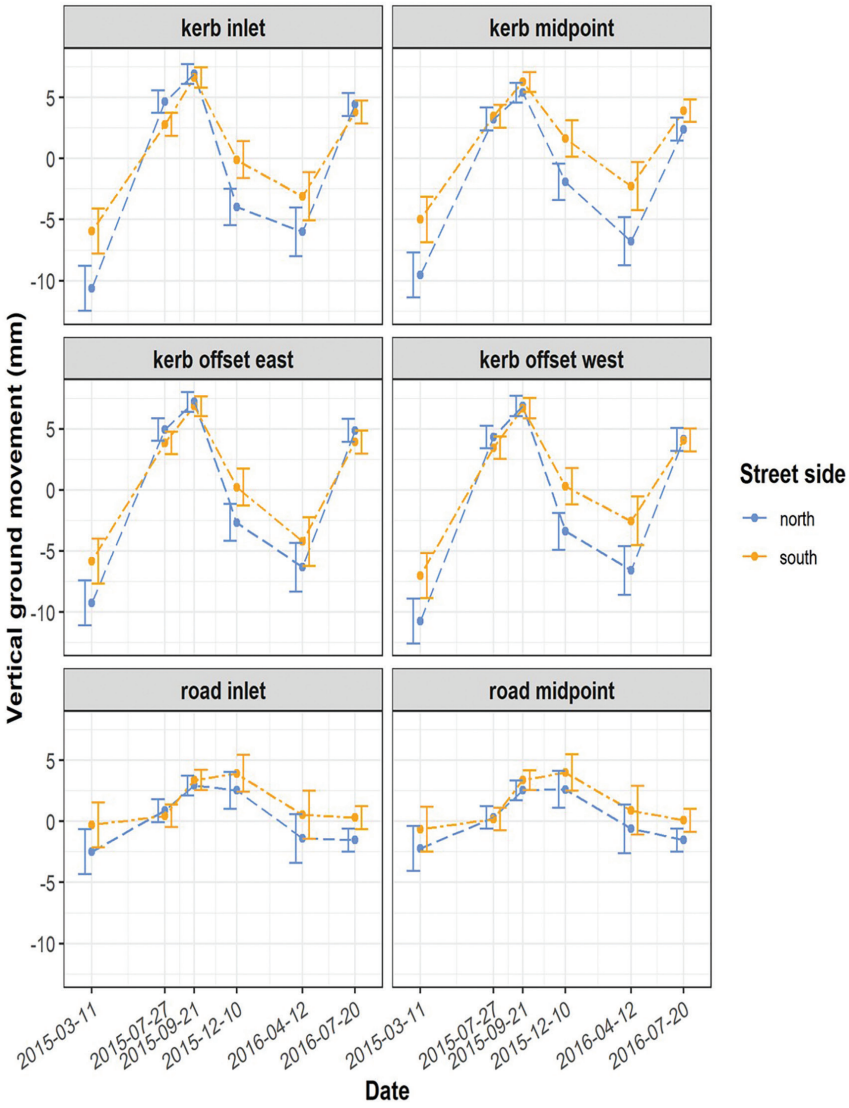

Figure 7. Adjusted mean vertical ground movement at different kerb and road surface survey point types on the north and south sides of the road on different survey dates. Error bars show half of the average LSD (5%); means with error bars that overlap are not significantly different.

moderately reactive clay did not increase ground movement.

The findings of this experiment are specific to the local climate, soil, and the design of the harvesting device and soakage well. The volume of stormwater harvested by the inlets may have varied and there may have been some partial clogging of inlets by leaves, and litter between road sweeping events may have reduced harvest volumes at some sites and times; however, the measured and modelled ground movement results suggests any impacts were negligible and inconsequential in terms of potential impact on built infrastructure. The experiment's 21-month duration provided a limited subset of the site's potential rainfall and evapotranspiration conditions, but the results covered periods of above average and below average rainfall. The results suggest that soils of similar or lower reactivity are unlikely to react to infiltration through kerbside harvesting devices and soakage wells.

The small amplitude of ground movement at the road surface was expected. The sealed road surface restricted infiltration into and evaporation from the road base and subgrade. Increased soil strength and reduced diffusion of gases in compacted soil beneath roads are known to deter root growth (Watson et al. 2014), so minimal infiltration and root related wetting and drying effects beneath the road were expected.

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These factors, and the separation distance between the road's subgrade and the verge surface, were expected to minimise change in water content in the subgrade. The extent of this buffering was sufficient to reduce and delay ground movement beneath the road, as the experiment shows.

Vertical movement at the road surface lagged movement at the kerb in some time intervals. On the south side of the road the kerb settled between 2015 September 21 and 2015 December 10 while the road surface underwent heave. Between 2016 April 12 and 2016 July 20 the kerb underwent heave and the road surface settled (Figure 6). The dates of maximum heave and settlement beneath the road were not as clearly defined as those at the kerb, probably due to lag.

Concern with water infiltration into reactive soil may be linked to observations that road seals which prevent water ingress coincide with reduced ground movement, as in this experiment. Reduced ground movement beneath the road may relate to diminished water loss through evaporation and transpiration, however, rather than to reduced infiltration. Greater ground movement on the northern side of the road than on the southern side, in the form of greater settlement on the north side, occurred on occasion at kerb inlets and kerb midpoints during and following the dry summer (Figure 7). Difference in ground movement may be due either to differences in soil reactivity or different rates of change in soil moisture, perhaps through extraction by trees. Significant variation in soil reactivity was unlikely given the road's width of 8 m and the distribution of experimental sites. The site survey identified more and larger trees on the north side of the road than on the south. Water extraction by trees is known to increase soil settlement (Biddle 1983; Cameron et al. 2006; Sun et al. 2022) and is the most likely reason for greater settlement on the north side of the road during dry periods.

In March 2015, the adjusted mean kerbtop level on the north side of the road was approximately 10 mm below the datum level and 4 mm below the April 2016 mean level. On the south side of the road, the kerbtop level was approximately 6 mm below the datum in March 2015 and 4 mm below the April 2016 mean level. These levels reflect below average rainfall in the 3 months before March 2015 and above average rainfall in the 3 months preceding April 2016. The difference in settlement between the north and south sides of the road at the dry points of 2015 and 2016 was consistent at approximately 4 mm despite considerable variation in rainfall. This difference in settlement between the north and south sides of the road in both high and low rainfall periods is consistent with water extraction by trees.

On 2016 April 12 there was greater settlement on the north side of the street at the kerb midpoints but there was no difference at the kerb inlets on this date (Figure 7). Average annual rainfall for January, February, and March is 64 mm, but actual rainfall in 2016 was more than double the average at 145 mm. The kerb inlet and kerb midpoint graphs in Figure 7 suggest that increased soil settlement in the presence of trees following the typically dry summer period was offset by the stormwater harvesting and infiltration through the inlet and soakage well during the wetter than average start to 2016, which is consistent with Goldfinch (1995) and with infiltration through permeable paving into moderately reactive soil in proximity to trees (Johnson et al. 2020). Further investigation of urban tree water use and geotechnical implications of infiltration is needed, particularly in relation to tree species growing in reactive soil.

The ground movement results (Figure 7) are identical on the north and south sides of the road following soil-water recharge during the wet period of the year; 6 mm above the datum on 2015 September 21 and 4 mm above the datum on 2016 July 20. The slightly lower 2016 level may be due to the shorter infiltration time, as the final survey occurred before the end of winter. Restorative heave to similar level on both sides of the road during the winters, from starting points of greater settlement on the north side, required greater infiltration on the north side (assuming similar soil reactivity), which is consistent with Johnson et al. (2020). This result, therefore, supports enhanced infiltration in the presence of trees (Bartens et al. 2008; Di Prima et al. 2020; Gonzalez-Ollauri et al. 2020).

No difference in the amplitude of ground movement at infiltration and midpoints, or in seasonal settlement during times of below average and above average rainfall on either side of the road, raises the question of whether it may be possible to infiltrate more water into the soil than was delivered during the experiment. Infiltrating water when evapotranspiration is high during summer months would help to offset soil shrinkage and settlement, but the effects of infiltrating a large volume of rainfall into reactive soil

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during winter, when rain is more plentiful and evapotranspirational demand is low, remain unknown.

Identical high ground levels at inlets and midpoints following the wet winter periods (Figure 7) supports the finding that infiltration did not increase ground movement. This consistent maximum seasonal heave achieved under above average and below average rainfall scenarios also raises questions. Would additional infiltration have resulted in greater heave? If so, what is the relationship between infiltration and heave at the wetter end of the soil water content range, or what is the infiltration capacity of the soil?

Longterm multidisciplinary research in different climatic zones, different soil types, and with different tree species and tree sizes is required to answer these questions. Alternative water sources and methods to restore soil moisture during dry periods and so maintain minimal ground movement during drought should be investigated. The potential to harness stemflow and hydraulic redistribution to harvest and distribute stormwater throughout avenues and stands of trees to minimise seasonal ground movement across their combined rootzones also requires further investigation, as it may help to reduce differential soil movement, increase stormwater harvesting capacity, and reduce damage to infrastructure. The potential to improve the performance of stormwater management using WSUD devices through inclusion of trees and other vegetation, particularly on reactive clay soils, warrants further investigation. Mitigation of the massive expense associated with reactive soil-related home and infrastructure damage suggests that funding this research should be prioritised.

These results show that concerns about the use of soakage wells and similar WSUD infiltration devices on urban streets contributing to increased ground movement and damage to infrastructure may be unfounded. In a bitumen sealed urban street with reactive soils, the presence of soakage wells did not cause significant ground movement and movement was similar in parts of the street with and without soakage wells. The research indicates that soakage wells without trees do not significantly alter ground movement, and so their use to facilitate urban tree growth and increase canopy cover at a time of climate change should be encouraged.

Further research is likely to reveal that this result is conservative and that opportunities exist to harvest and store larger volumes of stormwater in the soil for passive irrigation of urban vegetation. Multidisciplinary research is needed to investigate the effects of point infiltration of larger volumes of stormwater into all soil types, including highly reactive clays, in different climates over extended timeframes and with many tree species. As urbanization increases stresses on existing systems, scheduled renewal of ageing inner-city infrastructure will continue to present opportunities to further develop and test green engineering technologies

CONCLUSION

Stormwater harvesting and infiltration into reactive clay soil in a residential street did not increase ground movement at kerbs or road surfaces during periods of above and below average rainfall. Ground movement was of similar amplitude near infiltration points and at points distant from and unaffected by stormwater harvesting. Integration of trees and other vegetation with WSUD devices delivers substantial community and ecosystem service benefits, particularly in clay soils in which root growth increases water harvesting and storage. The contributions trees make to urban hydrology through canopy rainfall interception, stemflow, hydraulic redistribution, evapotranspiration, enhanced soil conductance through biopores, preferential flow paths along root channels, and enhancement of soil microbiota justify the inclusion of trees in WSUD devices and other green infrastructure.

The efficiencies with which the natural hydrological functions of trees can enhance stormwater management through WSUD, particularly on clay soils, are likely to see green infrastructure increasingly mandated in an expanding range of multifunctional urban applications. These results showed that dispersed, small scale stormwater harvesting and infiltration devices are suitable for widespread application in low to moderately reactive clay soil in semi-arid environments. Their widespread use will help to equitably deliver increased human and environmental benefit across communities with negligible risk.

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Résumé. Contexte: Les villes durables auront besoin d'une conception urbaine sensible à l'eau (CUSE) qui intègrera les arbres de rue, les sols urbains et les infrastructures techniques. Toutefois, on peut avoir l'impression que ces systèmes contribuent aux mouvements du sol, ce qui peut s'avérer problématique pour les infrastructures grises (en dur). Il est à craindre que le détournement de l'eau vers des systèmes de collecte (bassins ou puits) en bordure de trottoir pour les arbres de rue n'aggrave les mouvements du sol. Méthode: Vingt-huit petits systèmes de collecte des eaux pluviales en bordure de trottoir, qui détournent les eaux de ruissellement vers des bassins d'infiltration en bordure de rue, ont été répartis le long d'une rue résidentielle dans une banlieue proche de la ville d'Adélaïde, en Australie méridionale. Les bassins peuvent être aménagés avec ou sans la présence d'arbres de rue, mais leur verdissement permettrait d'obtenir des avantages plus importants sur le plan de la fonctionnalité et de l'environnement. Des mesures régulières du niveau du sol ont été effectuées afin de déterminer les mouvements du sol sur une période de deux ans, en comparant les sites avec et sans bassin d'infiltration. Résultats: Les résultats ont montré que la collecte et l'infiltration des eaux pluviales dans l'argile réactive du site n'ont pas augmenté les mouvements du sol au niveau du trottoir ou de la surface de la rue lors des périodes de précipitations supérieures et inférieures à la moyenne. Les niveaux de la bordure sont généralement restés dans les limites de +10 mm (soulèvement) et de −15 mm (tassement) par rapport au point de référence, et le mouvement au plus haut de l'asphalte de la rue n'a pas dépassé +7 mm ou −6 mm. L'ampleur maximale du mouvement du sol (la somme du soulèvement maximal et du tassement maximal) en tout point était de 26 mm, mais le mouvement typique pour 9 emplacements, dont 6 près des entrées, était de 4 mm. Les mouvements de terrain étaient d'amplitude similaire à proximité et à distance des points d'infiltration et n'ont pas été affectés par la collecte des eaux pluviales. Conclusion: La présence d'arbres dans les CUSE, particulièrement dans les sols argileux fins où la croissance des racines augmente la collecte et le stockage de l'eau, peut contribuer de manière substantielle à l'hydrologie urbaine grâce à l'interception des précipitations par la canopée, à la redistribution hydraulique, à l'amélioration de la conductance du sol par la création de bio pores et à l'écoulement préférentiel le long des canaux racinaires. Cette recherche expérimentale montre que la présence de bassins d'infiltration n'entraîne pas d'augmentation des mouvements de terrain dans les sols argileux réactifs.

Zusammenfassung. Hintergrund: Nachhaltige Städte erfordern eine wassersensible Stadtgestaltung (WSUD), die Straßenbäume, städtische Böden und technische Infrastrukturen einbezieht. Es kann jedoch der Eindruck entstehen, dass diese Systeme zu Bodenbewegungen beitragen, die für harte Infrastrukturen problematisch sein können. Es besteht die Befürchtung, dass die Ableitung von Wasser in Bordsteinaufangsysteme für Straßenbäume die Bodenbewegungen noch verstärken könnte. Methode: Entlang einer Wohnstraße in einem inneren Vorort der Stadt Adelaide, Südaustralien, wurden achtundzwanzig kleine Regenwassersammelsysteme am Straßenrand verteilt, die das Regenwasser in Sickerschächte am Straßenrand ableiten. Die Sickerschächte können mit oder ohne Straßenbäume genutzt werden, aber ein größerer Nutzen und Umweltvorteile ließen sich mit Vegetation erzielen. Es wurden regelmäßige Messungen des Bodenniveaus durchgeführt, um die Bodenbewegung über einen Zeitraum von 2 Jahren zu bestimmen, wobei Standorte mit und ohne Sickerschächte verglichen wurden. Ergebnisse: Die Ergebnisse zeigten, dass die Regenwassernutzung und die Versickerung in den reaktiven Lehm des Geländes die Bodenbewegungen an der Bordsteinkante oder an der Straßenoberfläche in Zeiten mit über- und unterdurchschnittlichen Niederschlägen nicht erhöht haben. Die Bordsteinhöhen blieben im Allgemeinen innerhalb von +10 mm (Hebung) und −15 mm (Setzung) des Bezugspunkts, und die Bewegung an der Oberseite der Asphaltversiegelung war nicht größer als +7 mm oder −6 mm. Das maximale Ausmaß der Bodenbewegung (Summe der maximalen Hebung und der maximalen Setzung) betrug an jedem Punkt 26 mm, aber die typische Bewegung an 9 Punkten, von denen 6 in der Nähe von Einlässen lagen, betrug 4 mm. Die Bodenbewegungen waren in der Nähe und in größerer Entfernung von den Versickerungspunkten ähnlich groß und wurden durch die Regenwasserbewirtschaftung nicht beeinflusst. Schlussfolgerung: Die Verwendung von Bäumen im Rahmen von WSUD, insbesondere in feinen Lehmböden, in denen das Wurzelwachstum die Wassergewinnung und -speicherung steigert, kann einen wesentlichen Beitrag zur städtischen Hydrologie leisten, da die Baumkronen Niederschläge abfangen, hydraulisch umverteilen, die Bodenleitfähigkeit durch die Schaffung von Bioporen erhöhen und den Abfluss entlang der Wurzelkanäle begünstigen. Dieses Experiment zeigt, dass das Vorhandensein von Sickerschächten nicht zu einer erhöhten Bodenbewegung in reaktiven Lehmböden führt.

Resumen. Antecedentes: Las ciudades sostenibles requerirán un diseño urbano sensible al agua (WSUD, por sus siglas en inglés) que integre el arbolado de las calles, los suelos urbanos y la infraestructura de ingeniería. Sin embargo, existe la percepción

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de que estos sistemas contribuyen al movimiento del suelo, lo cual puede ser problemático para la infraestructura física. Existe la preocupación de que la desviación del agua hacia sistemas de captación de aguas pluviales en las aceras para el arbolado de las calles pueda exacerbar el movimiento del suelo. Método: Veintiocho pequeños sistemas de captación de aguas pluviales en las aceras, que desviaban la escorrentía pluvial hacia pozos de absorción en las aceras, se distribuyeron a lo largo de una calle residencial en un suburbio interior de la ciudad de Adelaida, Australia Meridional. Los pozos pueden utilizarse con o sin la presencia de arbolado en las calles, pero se podrían lograr mayores beneficios ambientales y de utilidad con vegetación. Se realizaron mediciones regulares del nivel del suelo para determinar el movimiento del suelo durante un período de dos años, comparando sitios con y sin pozos de absorción. Resultados: Los resultados mostraron que la captación de aguas pluviales y la infiltración en la arcilla reactiva del sitio no aumentaron el movimiento del suelo en las aceras ni en la superficie de la carretera durante períodos de precipitaciones superiores e inferiores a la media. Los niveles de bordillo generalmente se mantuvieron dentro de +10 mm (levantamiento) y −15 mm (asentamiento) del datum de referencia, y el movimiento en la parte superior del sello de la carretera asfáltica no fue mayor de +7 mm o −6 mm. La extensión máxima del movimiento del suelo (suma del levantamiento máximo y el asentamiento máximo) en cualquier punto fue de 26 mm, pero el movimiento típico en 9 puntos, 6 de los cuales estaban cerca de entradas, fue de 4 mm. El movimiento del suelo fue de amplitud similar cerca y más lejos de los puntos de infiltración y no se vio afectado por la captación de aguas pluviales. Conclusión: El uso de árboles dentro de WSUD, particularmente en suelos arcillosos finos en los que el crecimiento de las raíces aumenta la captación y el almacenamiento de agua, puede contribuir sustancialmente a la hidrología urbana a través de la intercepción de la lluvia del dosel, la redistribución hidráulica, la conductancia mejorada del suelo a través de la creación de bioporos y el flujo preferencial a lo largo de los canales radiculares. Esta investigación experimental muestra que la presencia de pozos de infiltración no conduce a un mayor movimiento del suelo en suelos arcillosos reactivos.

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