Research Paper

Residential demolition and its impact on vacant lot hydrology: Implications for the management of stormwater and sewer system overflows

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HIGHLIGHTS

• Some cities have a coincident over-abundance of stormwater volume and vacant land.
• Demolition processes can alter the quality of vacant land.
• We assessed urban vacant land soils and their hydrology.
• Data was used to show how vacant lots could be used as infiltrative green infrastructure.

GRAPHICAL ABSTRACT

ABSTRACT

Increased residential demolitions have made vacant lots a ubiquitous feature of the contemporary urban landscape. Vacant lots may provide ecosystem services such as stormwater runoff capture, but the extent of these functions will be regulated by soil hydrology. We evaluated soil physical and hydrologic characteristics at each of low- (backyard, fenceline) and high-disturbance (within the demolition footprint) positions in 52 vacant lots in Cleveland, OH, which were the result of different eras of demolition process and quality (i.e., pre-1996, post-1996). Penetrometer refusal averaged 56% (range: 15–100%) and was attributed to high concentration of remnant buried debris in anthropogenic backfill soils. Both disturbance level and demolition type significantly regulated infiltration rate to an average of 1.8 cm h⁻¹ (range: 0.03–10.6 cm h⁻¹). Sub-surface saturated hydraulic conductivity (Kₛ) averaged higher at 4.0 cm h⁻¹ (range: 0.68 cm h⁻¹), was influenced by a significant interaction between both disturbance and demolition factors, and controlled by subsurface soil texture and presence/absence of unconsolidated buried debris. Our observations were synthesized in rainfall-runoff models that simulated average, high- and low-hydrologic functioning, turf-dominated, and a prospective green infrastructure simulation, which indicated that although the typical Cleveland vacant lot is a net producer of runoff volume, straightforward change in demolition policy and process, coupled with reutilization as properly designed and managed infiltration-type green infrastructure may result in a vacant lot that has sufficient capacity for detention of the average annual rainfall volume for a major Midwestern US city.

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1. Introduction

The rise of vacant land as predominant land cover in many urban core areas is attributed to the decay of urban residential housing stock. These circumstances of blight have been accelerated by recent trends in foreclosure, abandonment, and tax-delinquency (Whitaker & Fitzpatrick, 2011). According to the National Vacant Properties Campaign (Smart Growth America, 2005), vacant properties are distinguished by either or both of two general features: that the property is a nuisance or poses a threat to public safety; and the landowner neglects to pay taxes, defaults on the mortgage and utility accounts, and fails to keep the deed free of liens. One outcome of this confluence of economic conditions and land use is an increased number of residential demolitions with a correspondent increase in the proportion of vacant land. Although the literature is consistent in recommending careful analysis of the social, economic, and environmental costs (e.g., disposal of rubble, dispersion of asbestos or heavy metals in dust, reduced soil quality) or societal benefits (e.g., removing blighted properties, public safety) prior to demolition (Bullen & Love, 2010; O’Flaherty, 1993; Power, 2008), there is a trend toward wholesale demolition of blighted residential neighborhoods in cities like Cleveland, OH. From a purely economic standpoint, the oversupply of vacant land can depress the value of these vacant properties (and thereby potential for redevelopment). An alternative, productive reuse of vacant land is needed to arrest devaluation. Land bank agencies have emerged as a critical force in organizing the onslaught of vacant properties and setting the stage for a more coordinated re-use of vacant land toward urban agriculture (Masson-Minock & Stockmann, 2010) and the detention of excess stormwater volume.

Just as private parcels have some capacity to manage stormwater runoff volume with stormwater management retrofits (Keeley, 2007; Mayer et al., 2012), soils in vacant residential lots may also play a role (albeit passive) as an infiltrative sink for stormwater (Shuster et al., 2011; Xiao, McPherson, Simpson, & Ustin, 2007). On a neighborhood scale, stormwater infiltration and redistribution is a potentially significant ecosystem service, and may thereby impart more value to vacant land that presently has little or no value. On a larger scale, stormwater runoff volume that enters combined sewer systems (CSSs) serves to reduce system capacity, which leads to combined sewer overflow events (CSOs). The frequency and volume of combined sewer overflows have increased over the years due to aging infrastructure (cracked conveyances that allow exfiltration, infiltration and inflow), reductions in operation and maintenance budgets that would otherwise control infiltration-infiltration spills in the combined system; and that there has been no substantial change in the load on the CSS from increased directly connected impervious area and changing rainfall patterns due to climate change (Semadeni-Davies, Hernebring, Svensson, & Gustafsson, 2008). Enforcement actions aimed at repairing or otherwise reducing CSO frequency and volume have recently begun to incorporate green infrastructure (rain gardens, cisterns, green roofs, urban agriculture, etc.) as a way of keeping stormwater runoff volume out of the existing gray infrastructure (piped conveyances, inlets to CSS, a wastewater treatment plant, off-line storage, etc.). In practice, green infrastructure leverages plant-soil systems and other forms of storage to capture and detain stormwater runoff with an emphasis on the more frequent, smaller-depth storms. Green infrastructure strategies employed in this way may keep stormwater runoff volume out of the CSS, with the potential to thereby reduce CSO frequency and volume.

The substantial amount of vacant land available in these cities offers additional detention capacity for stormwater that would otherwise contribute to CSO events; with soils as the primary storage media. As Xiao et al. (2007) found, when infiltration capacity is exceeded, the production of surface runoff is initiated, and regulated by soil properties. Since there is no longer a residence on vacant lots, there is a great deal of pervious surface area for infiltration and redistribution of soil moisture, though the specifics of these processes may differ among parcels due to the influence of residential demolition processes. Furthermore, the imprinting of anthropogenic disturbance as the primary soil forming factor of vacant lot soils can alter soil properties by inversion of soil horizons, mixing of debris with fill or native soils, sealing, and compaction among other structural changes that affect site hydrology and drainage (Scalenghe & Marsan, 2009). Demolition techniques vary within a range of generally accepted practices that are designed to bring down a structure in a safe, expedient, and effective manner. An unforeseen consequence of these practices is the negative impact that demolition has on soils, which may affect infiltration and drainage patterns in vacant lots (Shuster et al., 2011). There is a dearth of data on urban soils with regard to their role in landscape hydrology, and especially for vacant lot soils, and our study has no known prior precedent. Our main objectives were to assess the soils and hydrology of vacant lots, and use this data to understand how extant conditions and demolition may modulate the suitability of vacant lots as infiltrative, passive green infrastructure. We assessed soil physical and hydrologic characteristics and how they are influenced by different levels of disturbance (as: lower (parcel area with remnant, undisturbed soils), higher (fill areas on vacant lots within the footprint of the structure)); and demolition technique (burying debris on-site versus removing debris); or if both factors influenced vacant lot hydrology. To advance the data to practical scenarios of actual and potential vacant lot hydrologic functions, we synthesized field data and findings in a rainfall−runoff model to quantify runoff volume from a typical vacant lot, and parameters were adjusted to illustrate the implications for redevelopment as green infrastructure, as one approach to decentralized urban stormwater and combined sewer overflow management in an urban core area.

2. Materials and methods

2.1. Site selection and site−level measurements

Soils and extant vegetation for a total of 52 residential vacant lots were assessed for physical, hydrologic, and chemical characteristics. This survey was conducted across the NEO2RD service area in 2010 (31 sites; Fig. 1), and then in 2011 focused on a two blocks in the Slavic Village neighborhood (21 sites; Fig. 1). The parcels characterized in 2010 were selected from an overlay (Arc GIS, ver. 10, ESRI Corp. Redlands CA) of maps of vacant, publicly owned residential parcels that were within the boundary of both the corporate limits of the City of Cleveland, and within the drainage areas for relatively low volume (<60 million yr−1), high frequency (>5 activations yr−1) Northeast Ohio Regional Sewer District (NEORSD) combined sewer drainages, as in Shuster et al. (2009).

For the greater Cleveland area, there are two distinct eras of standard demolition practice: The pre-1996 demolition technique involved demolishing the residence, bulldozing the entirety of the demolition debris into the basement−foundation, covering the debris with a layer of clean fill soil, and completed with seeding in order to provide permanent stabilization as turf cover. The post-1996 demolition was more extensive and entailed the demolition of the residence, basement, and foundation, removal of all of the resultant debris, backfilling the excavated area with clean fill soil, and seeding in order to provide permanent stabilization as turf cover (see: OAC Chapter 1510:15−1.B(38), http://codes.ohio.gov/oac/15013A15−1). In the absence of complete site histories for pre-1996 demolitions, these were distinguished from post-1996 vacant lots by a distinctive slumped fill area in the footprint of the former residence.
For both types of demolitions, each lot was divided into two zones, a lower- and higher-disturbance subarea (Fig. 2). We designated the rear of the backyard (near the rear-most utility right-of-way) as the lower-disturbance subarea of vacant lots. Alternately, the higher-disturbance subarea was defined as the footprint of the former residence. This higher-disturbance was attributed to the initial demolition, excavation and removal of the foundation and basement area, and import of fill to backfill the excavation (post-1996 demolitions only). At each of 13 uniformly spaced points set within an “X” transect on the parcel, we estimated the prevalence of buried debris at the site level by driving a length of ~2 cm diameter steel reinforcing bar with a 5 lb hammer, and recorded the number of blows (up to a maximum of 30 blows, with one person designated for this task) to refusal or a maximum depth of 0.66 m. The percent refusal is defined as the proportion of sites sampled that registered refusal to the total number of points sampled. For each lot, the mean depth of refusal was determined by averaging the bar length measured at each sampling point where refusal was encountered.

2.2. Subarea measurements: soil taxonomy, hydrology, chemical

Soil cores (6 cm diameter, 1.3 m long) were extracted with a truck-mounted Geoprobe 5400 (Geoprobe Systems, Salina, KS) in each of lower- and higher-disturbance subareas, and to depth of refusal. Core samples were inspected in the field to locate the transition between soil diagnostic horizons or layers to the hydraulically restrictive soil layer (HR; i.e., the first impeding layer) by morphologic cues (change in color, texture, location of impeding layers, etc.), and the percent rock or debris fragments was estimated. Soils in core samples were also classified in the field according to soil survey standards from the National Soil Survey Handbook [Section 627.08(d)2] and the Soil Survey Manual (USDA, 1993), and Keys to Taxonomy (Soil Survey Staff, 2010). A second borehole was developed to the depth of the hydraulically restrictive soil layer as it was identified in the morphological evaluation. The saturated hydraulic conductivity of this HR horizon was measured with a compact constant head permeameter (CCHP or Amoozometer; Ksat, Inc., Raleigh, NC). Water flux data collected from the CCHP was used to calculate $K_{sat}$ via Eq. (1):

$$K_{sat} = AQ$$

where $K_{sat}$ is the subsurface hydraulic conductivity ($K_{sat, sub-surface}$), $A$ is a constant based on the radius and head of water in the

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**Fig. 1.** Maps indicate locations of vacant lots assessed in this study. The main map plot assessments made in 2010 (Greater Cleveland), and the inset plot assessments made in 2011.

**Fig. 2.** Each vacant lot was assessed by disturbance level (subareas), and penetrometer measurements were made at each circle along an “X” transect.
borehole, and Q is the steady-state rate of water flow into the borehole (Amoozegar, 1989). The method addresses the equilibrium outflow of water from the borehole in a quasi-spheroidal geometry, and is therefore an approximate measure of subsurface redistribution of soil moisture and drainage. Within each of lower- and higher-disturbance subareas, one measurement of field saturated hydraulic conductivity was made with double-ring methods run in a falling-head mode; and two measurements of near-saturated surface hydraulic conductivity $K_{s\text{sat}}$ (~2 cm) were made with tension infiltrometers run at a suction head of 2 cm (Mini-Disk Infiltrometers; Decagon Devices, Pullman, WA). This technique served to exclude high variation in $K_{s\text{sat}}$ due to structural cracks and other macroporous sinks for flow, and emphasized the measurement of matrix flow into surface soils. The surface $K_{s\text{sat}}$ was calculated according to manufacturer-recommended methods. Soil was subsampled from the cores at the surface and hydraulically restrictive horizons and particle size analysis on these samples determined with the pipette method (Gee & Or, 2002) with hydrogen peroxide treatments to remove organic matter.

### 2.3. Statistical analysis

To correct departures from normality and equal sample variance, all univariate data was rank transformed prior to analysis of variance (ANOVA). An overall MANOVA (proc glm; Statistical Analysis System, ver. 9.3) was performed to determine if there were significant disturbance, demolition, or interactive effects for at least one of the variables measured (Wander & Bollero, 1999). Rank-transformed univariate data were next subjected to two-way ANOVA (proc glm; Statistical Analysis System, ver. 9.3) to determine significance of demolition type ($D$), subarea ($S$), or their interaction ($D \times S$), and univariate least-squares means were calculated from untransformed data. We specified type-III sums of squares to allocate the effects of unequal sample sizes. Where covariates were used, we employed analysis of covariance (ANCOVA; proc glm; Statistical Analysis System, ver. 9.3). Inverse subsurface $K_{s\text{sat}}$ data was treated as a categorical variable and included in the class statement of the ANOVA model. The threshold of significance for all tests was set at $p \leq 0.10$. The MANOVA criterion was met, as we rejected the hypothesized absence of a significant disturbance x demolition interaction ($p = 0.98$); and hence protected serial ANOVA were run for each variable (Scheiner, 1993). The reader is encouraged to interpret significance of serial ANOVA tests in the context of possible inflation of Type I error. Data was graphed in SigmaPlot 11.0 (Systat Software Inc.; San Jose, CA).

We applied the USEPA Storm Water Management Model (SWMM; ver. 5.0.022) to estimate comparative runoff volume from a range of vacant lot conditions. We used parameters that reflect an average vacant lot based on measured landscape conditions and hydrologic measurements; low, high hydrologic function; complete turf cover, and projected outcomes with infiltration-type green infrastructure.

The models are forced with the 36 years of rainfall (Cleveland WSFO Airport 1970–2006 record, average annual rainfall depth of 952 mm, hourly temporal resolution, collated from USEPA National Stormwater Calculator, ver. 1.0.0.8), which is the standard rainfall record for all district modeling efforts. Models were constructed as a single sub-catchment area with an area of 0.03 ha and a overland flow path 10 m in width, which was the average area and width of vacant parcels assessed in Cleveland, OH. Remnant total impervious area from incomplete demolitions was estimated by observation (Table 1). Runoff was generated in each instance with the SWMM Green-Ampt infiltration sub-model (such that: soil suction head $\Psi_{\text{matric}} = 25$ cm, measured saturated hydraulic conductivity of surface soils (as $K_{\text{sat}}$, cm h$^{-1}$) varied depending

<table>
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<th>Low</th>
<th>Turf</th>
<th>GI</th>
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<td>10.60</td>
<td>0.03</td>
<td>1.00</td>
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3. Results and discussion

#### 3.1. General vacant lot environment and surface soil conditions

We assessed vacant lots located in East Cleveland (Euclid–Green, Forest Hills, Glenville, Hough South Collinwood, St. Clair–Superior), South Cleveland (Kinsman, North Broadway, South Broadway, Tremont, Union–Miles Park), and West Cleveland (Ohio City and Puritas–Longmead). According to historical records, houses in these neighborhoods were constructed between 1881 and 1921 (Hopkins, 1881, 1914, 1921). The limit of disturbance around a house probably was not much larger than the actual foundation, because basement excavations and site grading was done primarily by hand labor (Gillette, 1908; McDaniel, 1919); and mechanized excavators were used only for larger, commercial types of construction (Mankeloo, 2004). The houses were constructed using locally available construction materials for the time: bricks, cinder block, concrete, and wood (US Department of Housing and Urban Development, 2001).

Our sample set included a total of 52 vacant properties, 15 of which were demolished prior to 1996, with 37 vacant lots the product of post-1996 demolition practices. On the whole, we observed that typical and legacy demolition practices have had negative impacts on ease of re-use and restoration, and overall vacant land hydrologic status. On average, penetrometer refusal (due to buried debris) was encountered at 56 ± 3 cm (SE, standard error of the mean) percent of sampling positions (Fig. 3), and at a depth of 12 ± 1 cm. Although percent refusal was not significantly affected by disturbance subarea (57 ± 5 and 56 ± 5% for lower- and higher-disturbance subareas, respectively), demolition type was greater ($p = 0.03$) for pre-1996 ($64 ± 6$%) than post-1996 ($49 ± 4$%) demolitions (Fig. 3). We observed a consistent depth of refusal among disturbance levels, and there was a small, but significant ($p = 0.04$) decrease in the depth of refusal from pre-1996 ($14 ± 1$ cm) to post-1996 ($12 ± 1$ cm), which indicates that debris was buried slightly deeper in post-1996 demolitions. Theoretically, the soils outside of the construction envelope should not show substantial evidence of influence from anthropogenic activities. Based on the lack of a significant disturbance subarea effect, it appears that the impact of demolition extended beyond the envelope of the residential footprint to affect the whole of the parcel. Despite the specification requirement for debris removal for post-1996 properties, and backfill of the excavation with clean fill, these vacant lots still presented with shallow refusal nearly half of the time. The side-yard (left or
right side of the lot) typically served as a location for a driveway, which terminated in a pad or garage structure. The demolition of these concrete surfaces was often incomplete, increasing both the supply of debris and the proportion of parcel area as intact impervious area. The percent rock and debris fragments in the surficial part of soil borings averaged 54%, with no significant differences on the basis of subarea disturbance or demolition. This suggests that the difference in refusal between demolition types is likely due to demolition debris, rather than rock fragments imported with fill material. Soil borings indicated that shallow-buried demolition debris is common, and from a restorative standpoint, the debris would need to be removed for prior vacant land re-purposing efforts. However, building and construction codes were less stringent during this time (US Department of Housing and Urban Development, 2001), so it is still possible that soils were backfilled without regard to maintaining the order of the native soil horizons, and construction debris was likely used as fill material and buried on-site. In addition, the types of excavators used in the demolition process could barely fit on the vacant lot property, and required the operator to make multiple passes and turns, which may have served to grind debris down and into an already compacted fill soil.

Overall, we found that demolition procedures involved neither the removal of demolition debris and disposal off-site, nor a final grading, as per the specification that the contractor “shall provide a finished site that is level and free of debris.” (Personal communication: City of Cleveland, Department of Building and Housing, Demolition Bureau). Demolition produces substantial amounts of debris, all of which requires disposal. For any pre-1996 demolition, the point of clean-up is moot, as debris burial was an accepted practice at that time; and post-1996 demolitions still left debris, which was found buried throughout the lot area. Overall, the spatial extent of the demolition affected the whole of the parcel area (except for the relatively undisturbed area in the farthest reaches of the backyard), not just the residential footprint. The combination of incomplete removal of debris and the greater extent of adulteration of soil with debris immediately adds to the cost of the original demolition (which averages (US 2010 $) $7500 in Cleveland, OH; pers. communication, D. Borkowski, June 2010). The City of Cleveland’s demolition requirements specify that “the event that the contractor shall bury debris outside of sub-grade portions of the structure...shall fail to remove the same...the City shall take whatever steps are required to re-excavate and properly dispose of the improperly buried debris,” with the costs of this extra effort to be billed to the original contractor. However, it is readily apparent that the City of Cleveland could not provide sufficient staffing—with over 28,000 vacant lots in local land banks—to provide for proper inspection and oversight in the administration of the demolition process. These circumstances can increase the risk that any given vacant lot will not be re-visited, post-demolition, to ensure adherence to current specifications, much to consider the vacant space for its re-use opportunities.

Since there are no records of the specific demolition process and outcomes, and the soil specifications are non-specific in its definition of “clean fill”, it is impossible to ascertain the source(s) of fill material for the demolitions included in our sample set. Sourcing fill soils appeared to be largely opportunistic. Fill material was varied and ranged from well-graded quarried sands to soils imported from road cut-and-fill projects or excavations. The soils tended toward moderate to well-drained, though the range in texture was broad with poorly drained fine-textured lacustrine silt loam to clay loams (Coarse-loamy, mixed mesic Aquic Udorthent), well-drained sandy loams (Coarse-loamy, mixed mesic Oxyaquic Udorthent), and construction debris with large particle size (ca. 0.3 m along the longest axis). Demolition type was the main control on soil textural separates such that surface soils had significantly more sand (61 ± 3 than 54 ± 2%; p < 0.05), less silt (25 ± 2 than 32 ± 1%; p < 0.01), and the same proportion clay (14 ± 2%) for pre- than post-1996 demolitions, either of these soils within the range of a sandy loam. With regard to local demolition specifications for soil fill, the average backfill material was not qualitatively “clean fill” due to the large amounts of shallow-buried debris.

On the other hand, the typical texture of vacant lot soils would be acceptable with regard to the vague textural specific further as “sand, clay, or loam” (City of Cleveland, Department of Building and Housing, Demolition Bureau).

Demolition activities were qualitatively most impactful around the footprint of the former residence, and less so for perimeter areas of a given lot. On a qualitative, observational level, poor effort and carry—in to establish post-demolition vegetative cover apparently left large areas of the vacant lot as bare space. Bare soils suggest the predominance of disturbed surfaces that can impede infiltration, and act as a barrier to seed germination (Scalenge & Marsan, 2009), both of which can inhibit the initial and future efforts to create a protective vegetative cover. Even though demolition contractors are required to insure “that grass is growing on the site...and that the site may be safely mowed.” (City of Cleveland, Department of Building and Housing, Demolition Bureau), most sites had incomplete turf cover. A notable exception, however, is the Slavic Village Development (SVD) sites characterized in 2011 (a total of 21) that collectively had at least a well-established turf cover. In some SVD lots, the lot was not only re-vegetated and exhibited good cover, the frontage was demarcated with a tall berm that was planted in sedges and a line of trees to discourage the entry of vehicles into the vacant lot. This indicated that key factors in ensuring that demolitions are properly finished and vacant lots re-vegetated include oversight and active advocacy from local citizen groups (e.g., the Slavic Village Development Corporation).

3.2. Surface hydrology of vacant lots

The estimated field-saturated hydraulic conductivity ($K_{sat,field}$) for surface soils averaged $48 ± 4$ cm h$^{-1}$, with a minimum of 0 and maximum of 225 cm h$^{-1}$. Where field notes indicated that the measurement was made on a sealed soil surface, $K_{sat,field}$ tended to be low, or register no measurable conductivity. By comparison, mean $K_{sat,field}$ was at least an order of magnitude higher than the maximum found by Hamilton and Waddington (1999) for a set of Pennsylvania residential lawns, and similarly higher than $K_{sat,field}$ determined by Gregory, Dukes, Jones, and Miller (2006) for compacted urban soils. Our inordinately high values of field $K_{sat}$
suggest that we measured bypass flow through surface-connected cracks in the soil profile or flow through large structural voids created by construction debris. Infiltration measured with double-ring infiltrometry may not be appropriate for urban locations where an accurate measurement is complicated by debris-laden, cracked surface soil conditions, producing inconsistent test conditions and data.

The mean matrix unsaturated hydraulic conductivity (at −2 cm hydraulic head, hereon $K_{unsat}$) was $1.8 \pm 0.2$ cm h$^{-1}$ (range: 0.03–10.6 cm h$^{-1}$), which is consistent with the coarser sandy loam textures found in these vacant lots. Since this measurement is made at near-saturation, it excludes the contribution of macropores and highlights matrix flow processes, and is interpreted as a conservative estimate of field infiltration rate. Disturbance level had a significant ($p = 0.04$) influence on $K_{unsat}$ with the more highly disturbed, fill subarea measuring at a rate of $2.4 \pm 0.3$ cm h$^{-1}$, and the less-disturbed area at a lower rate of $1.7 \pm 0.3$ cm h$^{-1}$ (Fig. 4). Demolition type also had an impact ($p = 0.09$) on $K_{unsat}$ with an average rate of $2.6 \pm 0.3$ cm h$^{-1}$, and $1.5 \pm 0.2$ cm h$^{-1}$ for sites demolished by pre- and post-1996 era demolitions, respectively (Fig. 4). The mean $K_{unsat}$ was maximized for the higher-disturbance subareas, which were also sandier, and slumping in the pre-1996 demolitions indicated that subsoils were not as compacted. These features that can promote higher hydraulic conductivity may have offset the protection against surface sealing (which can impede infiltration) afforded to the lower-disturbance post-1996 plots by protective herbaceous and turf cover.

3.3. Sub-surface hydrologic processes in vacant lots

We measured hydraulic conductivity in boreholes set at the depth of the first hydraulically restrictive layer. The hydraulically restrictive layer in the lower-disturbance subareas were typically composed of low-permeability silty clay loam lenses and dense lacustrine deposits, and residual soil horizons that formed from the underlying silstone bedrock (i.e., flat channers), each of which can act to impede both the downward flow of water and the redistribution of soil moisture. Within the highly disturbed fill subareas we found deposits of textiles, ceramics, wood, asphalt, crushed stone, concrete, slag, bituminous gravels, and cinders, all of which were interspersed with silty clay loam anthropogenic fill. For the lower-disturbance subareas, we observed fragments of native shale, quartz, gravel, and the rare deposit of buried textile materials. These lower-permeability deposits showed poor drainage soil color cues indicating historically wet, reducing conditions (Munsell color range 10YR 6/1, gray; to 10YR 8/1, white). Alternately, several vacant lots on the east side of Cleveland did not have a restrictive layer, as these exhibited well-drained anthropogenic fill overlaying native Aeolian sands (the shallower portion of stratified sand dunes), among other highly permeable deposits. These soils exhibited highly oxidized coloration (10YR 5/4, yellowish-brown to 10YR 2/2, very dark brown). As a consequence of the variable composition of these urban subsoils, subsurface $K_{sat}$ ranged between 0.0 and 68.2 cm h$^{-1}$ with a mean of $4.0 \pm 0.9$ cm h$^{-1}$.

A significant interaction between disturbance level and demolition type ($p = 0.10$) regulated subsurface $K_{sat}$ (Fig. 3), such that pre-1996 highly disturbed fill areas had the highest rates at $11.6 \pm 2.3$ cm h$^{-1}$, followed by post-1996 less-disturbed subareas at $6.9 \pm 2.4$ cm h$^{-1}$, and more similar for post-1996 demolitions, with $2.1 \pm 1.5$ and $1.9 \pm 1.5$ cm h$^{-1}$ for higher- and lower-disturbance subareas, respectively (Fig. 5). Although this interaction was accompanied by highly significant effects for both disturbance subarea ($p < 0.05$) and demolition type ($p < 0.01$), we consider only the highest-order interaction in our interpretation of these observations. The interaction between disturbance and demolition era effects are further explained by significant co-factors (ANCOVA: $p < 0.05$) including: time to equilibrium for the borehole infiltration test ($T_{equil}$), categorical infinite borehole $K_{sat}$, subsoil texture and coloration (e.g., presence/absence of construction debris), and depth to the first hydraulically restrictive layer.

The time to equilibrium ($T_{equil}$) for the borehole infiltration test was significantly affected by disturbance subarea only ($p < 0.005$), with a slower $T_{equil}$ in the lower- than higher-disturbance subareas at 35 ± 3 and 23 ± 3 min, respectively. The hydraulic condition at $T_{equil}$ is approximately saturated conditions in the soil surrounding the borehole measurement. A longer $T_{equil}$ may indicate more finely textured soils with less unconsolidated buried debris (at a depth of ~1 m) in the less-disturbed site areas, whereas a shorter $T_{equil}$ is found in the more highly disturbed subareas. As for the latter condition, borehole $K_{sat}$ was maximized, and suggests subsurface soils composed of unconsolidated demolition debris, coarser-textured soil materials, or a combination thereof. This dynamic in $T_{equil}$ is confirmed in part by the impact of demolition type on subsoil texture ($p < 0.01$) in the zone of hydraulic restriction, such that pre-1996 subsoil was typically coarser in texture (sandy loam, 60% sand, 28% silt, 12% clay) than that found in post-1996 vacant lots (loam, 47% sand, 38% silt, 15% clay). Many of the older demolitions were done to alleviate blight on the East Side of Cleveland where sandier soil predominated, and the more recent demolitions done farther...
west in neighborhoods like Slavic Village, where the effects of the recent foreclosure crisis were more pronounced.

Out of a possible 109 measurements, 8 of these registered infinite subsurface \( K_{\text{sat}} \), and employed as a categorical indicator variable. In the specific case of borehole infiltration tests registering infinite borehole \( K_{\text{sat}} \), the rapid fluxes were observed because either: (1) the measurement was made in a highly disturbed subarea where buried unconsolidated debris and fill soil created large void spaces, which allows unrestricted flow of water; or (2) subsolos in either low- or high-disturbance subareas having a coarse, sandy native soil texture that allows a similarly rapid water flux. Subsoil texture ranged from a less-permeable silt loam fill with a high content of construction debris, to highly permeable Pleistocene, glacio-fluvial sands or gravels and aeolian sands. Where demolition rubble was allowed to remain in the basement, the mean borehole-subsoil \( K_{\text{sat}} \) was much greater than both its lower- and more highly disturbed post-1996 (where basement and debris was removed) demolition counterparts. The type of demolition was therefore a key predictor of whether there was high hydraulic conductivity in the subsoil.

Although there was no difference in the depth to the hydraulically restrictive soil layer by subarea \((p > 0.10)\), demolition type significantly affected this depth metric \((p < 0.01)\) with the hydraulically restrictive zone in pre-1996 demolitions found at an average \( 110 \pm 6 \) cm depth, compared to a shallower \( 92 \pm 4 \) cm in post-1996 demolitions. The difference of \(-20 \) cm in restrictive depth may directly reflect the relatively low degree of packing in pre-1996 demolition practice compared to post-1996 methods. For the later-era demolitions, fill soil was typically placed in lifts, one truckload at a time, and spread around and compacted with either an excavator bucket or skid loader, all of which would systematically create compacted layers.

Overall, the interactive effects of disturbance and demolition process created contrasts in connectivity between surface and sub-surface hydrology. This was especially the case for the more highly disturbed areas demolished with pre-1996 techniques, which imparted a karst-like hydrologic artifact (Kaushal & Belt, 2012) throughout neighborhoods. The sub-surface of these lots had massive void space and capacity for water storage, could store water, and thereby act as cisterns. However, infiltration rates may restrict the amount of water that could ultimately percolate into and be stored in these anthropogenic cistern-like features.

3.4. The hydrologic role of different types of Cleveland vacant lots

We used a rainfall-runoff model to synthesize measured (e.g., \( K_{\text{unsat}} \)) and tabular values (e.g., Mannings \( n \)) to parameterize the model, illustrate the hydrologic conditions for each of average, high, low, turf, and prospective green infrastructure scenarios, and then use the output to compare functionality of different vacant lot conditions on the basis of limiting the production of runoff volume. For average lot conditions across all vacant lots (Table 1 and Fig. 7), the typical Cleveland vacant lot is a net producer of runoff, and a single 0.03 ha (i.e., 300 m\(^2\)) lot can generate an average of \(-3800 \) yr\(^{-1}\) of uncontrolled runoff. For a sloped vacant lot with complete coverage in herbaceous vegetation, and the study-wide maximum \( K_{\text{unsat}} \) (Figs. 6a and 7; Table 1), mean annual runoff volume was also
estimated to be ~38001yr⁻¹. The vacant lot with lowest hydrologic functionality (Fig. 6b), had the overall lowest \(K_{unsat}\) (Table 1), due in part to its large proportional area as bare, weathered soils, and higher percent total impervious area. Therefore, this type of vacant lot had the overall greatest average runoff volume of 75,242 yr⁻¹ (Fig. 7). On the other hand, the turf-cropped vacant lots (Table 1) that were commonly found along 72nd St. (Slavic Village, Cleveland, OH) were nearly level, had higher capacity for abstraction due to the uniform vegetative cover, and produced an average of 1130 yr⁻¹ of runoff volume (Fig. 7). Alternatively, a typically sized lot is set into infiltration-type green infrastructure by setting model parameters to reflect a nearly level grade, increased storage in a landscape depression (as a broad, shallow bowl, with a maximum depth of 10 cm in the center), and an increased resistance to overland flow with Manning’s n set to reflect a dense vegetative cover that is tall enough so that flow depth is always less than that of vegetation. Under these enhanced GI conditions, there is a further mitigation of infiltration-excess runoff formation processes (Table 1). For the GI scenario, the rainfall-runoff model estimated no runoff events, suggesting complete detention of the average annual Cleveland, OH rainfall record (Fig. 7).

There are several factors that promote the formation of runoff from the average vacant lot. We observed incomplete protection of the soil surface as vegetative cover can prevent interception and initial abstraction of rainfall, which consequently lowers the resistance to overland flow. Although moderate in magnitude, the average surface hydraulic conductivity does not allow for all precipitation to infiltrate prior to the onset of runoff production via infiltration-excess. Once runoff is produced, the grade of the typical vacant lots routes runoff volume to the combined sewer system. At the time of construction of the original residence, lot grade was canted toward the street, so as to facilitate overland flow over the curbs, and flow into street inlets that are the entry point for runoff volume into the combined sewer system. The majority of Slavic Village vacant lots sampled in 2011 were left nearly level by a more thorough demolition process (the result of good oversight from the local community development corporation). Otherwise, the grade of the average vacant lot was not changed (i.e., leveled) from its prior grade by demolition. Our simulation results suggest that there is sufficient infiltration capacity for both average and high-hydrologic functioning vacant lots such that they produce only modest annual volume of runoff, though there is still some degree of profile-control on the infiltration process, and therefore some runoff will be produced through infiltration-excess. As for the low-functioning vacant lot, the weathered soil surface may act like impervious surface. Although we attempted to account for higher depression storage as the slumped fill subareas of pre-1996 demolitions, the land cover and condition suggested that runoff would be produced earlier and for a longer period of time for an event, increasing the total annual anticipated runoff volume. The larger amount of runoff volume produced is one consequence of a low proportion of vegetative cover, and so there is furthermore little resistance to any overland flow that is created by an overall lack of infiltration opportunities. In spite of lower pervious depression storage (Table 1), which can decrease the initial abstraction of rainfall, the hydrology of the turf-dominated vacant lot is apparently dominated by profile-control of infiltration, with little runoff volume expected from the long-term rainfall pattern (Fig. 7).

By comparison with the average, and high-hydrologic functioning vacant lots, our data indicate that vacant lots with a \(K_{unsat}\) of at least 1 cm h⁻¹ and complete vegetative cover set on a level slope may yield excellent hydrologic function as-is. These vacant spaces are expected to detain nearly all runoff. However, we modeled the average and extremes of the sample set of Cleveland vacant lots, and 17 (about one-third) of the total number of lots assessed were below average, at least in terms of a \(K_{unsat}\) (in both the higher- and lower-disturbance subareas) often much less than 1 cm h⁻¹, and usually presenting with slope, a high proportion of spotty vegetation and bare space, and little depression storage capacity. Taking the modification of a vacant lot a step further (as in the GI example, Table 1) to minimize slope and maximize pervious area, increase resistance to flow through complete vegetation, increase depression storage depth, and bring the \(K_{unsat}\) above our estimated threshold predicts a vacant lot that contributes no runoff to the centralized wastewater collection system. Prospects for drainage and redistribution of the infiltrated water within at least the highly disturbed subarea would vary with the composition of the subsurface, which we discovered to be a widely ranging mix of soil and debris. Due to the expense of debris removal, it is unlikely that the hydrologic attributes of the subsurface would be improved upon. Yet, given the cisterm-like architecture found mostly in the highly disturbed areas and pre-1996 demolitions, storage and drainage may be relatively unlimited. These circumstances would suggest high potential for accommodating the rainfall that is infiltrated and percolates into unconsolidated fill materials, which themselves possess high storage capacity in void spaces. Over the long-term, the potential for detention in managed vacant lots appears to be quite high, though simulation with hourly rainfall data may introduce some artifacts to the model output. Hourly rainfall data is relatively coarse for simulations of urban catchments, and this is due to the typical predominance of impervious surface. The lack of infiltration losses can create conditions where runoff is produced shortly after the onset of a rainfall event. The time of concentration for runoff is therefore much less than the hourly time step of the simulation. This circumstance suggests a possible uncertainty in the estimation of detention, and due to the dynamic relationships between rainfall-runoff (e.g., routing, accounting for antecedent conditions). As for controlling uncertainty in rainfall data, it is only recently that rainfall records with higher temporal resolution have become available. This is attributed to both the awareness of the value of higher-resolution data, and progress in affordable instrumentation that facilitates accurate monitoring of inputs to local water cycles. What we gain from the present, long-term simulations is an indication of comparative detention performance among different hydrologic conditions in vacant lots.

Given that there are in excess of 28,000 vacant lots throughout the Cleveland combined sewer service area, the total runoff volume produced by vacant lots may serve to reduce local combined sewer system capacity. This is in addition to runoff volume contributed by streets and other directly connected impervious surface, and may increase the system-wide risk of CSO activity. In addition, to take the benefits of this type of environmental restoration and provide sufficient reductions in stormwater reduction to provide other ecosystem services (e.g., large-scale habitat, improvement to receiving waters) would require high a level-of-effort to transform equivalently large landscape areas to green infrastructure (Walsh, Fletcher, & Burn, 2012). On the other hand, the massive land area as vacant lots presents at the proper spatial scale to comprise a significant decentralized stormwater control measure. At the parcel level, however, in order to gain efficiencies in moving a derelict house through demolition and into green infrastructure, the desired landscape features should be realized at the time of demolition through an emphasis on vegetation than stabilization (USEPA, 2013). This process would include: (1) the specification of removing and recycling all demolition debris; (2) slanting the sub-grade slightly toward the back of the lot to encourage redistribution toward the rear of the lot rather than lateral movement of water which may impact on neighboring basements; and (3) using a debris-free, structured soil for fill, and laying in these soils to provide a stable base without over-compaction; and (4) re-vegetation with a plant community that has high functional diversity (variety
in root and canopy architecture) to protect the soil surface, build soil structure, and set deeper roots to encourage the improvement of drainage. This approach views the life-cycle of a vacant lot more flexibly by building in passive reutilization to yield a landscape that is a net absorber of precipitation. This restoration process is a start toward re-aligning the urban hydrologic cycle toward a pre-development setting.

4. Conclusions

Our assessments centered on gathering soil hydrologic data to objectively judge the suitability of vacant land for re-use in detention of excess stormwater runoff. We found that both disturbance level and demolition practice had significant impacts on soil properties that revealed implications for surface- and sub-soil hydrology. Our data suggests that debris-laden and compacted fill soil layers, ineffective attempts at re-vegetation at the time of demolition, and surface soil texture and vulnerability to sealing/compaction are all impediments to fully leveraging vacant lots toward its role as a decentralized infiltration opportunity in the urban hydrologic cycle. Lower- and more highly disturbed areas had similar and sometimes very high subsurface hydraulic conductivity, though due mostly to the relative degree of structural macroporosity (e.g., as debris in pre-1996 demolition subsoils) versus soil textural (e.g., sandier soils) control over drainage. Demolition practice correspondingly requires revision to promote complete removal of the structure and debris, placement of appropriate fill soil material, and establishment of a protective vegetative cover to promote a shift from runoff production to infiltration opportunities. Runoff modeling supports improvements to the demolition process, which should aim to preserve any existing soil and hydrologic attributes of vacant lots. This approach lays the groundwork for flexible re-use of vacant land for the implementation of green infrastructure as decentralized stormwater management. Given larger scale of landscape transformation, ecosystem services (increased green space, pollinator habitat, etc.) may be extended to areas historically lacking in these attributes. The assessment protocol used in this study are applicable to urban landscapes in other cities and soils, and should be used to determine site-specific circumstances, which will inform recommendations for demolition and water resources management in otherwise underutilized urban landscapes.

References

documents/true-costs.pdf