A 3D assessment of urban aquifer vulnerability using geological and buried asset models: Knowsley Industrial Park, NW England

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ABSTRACT

Knowsley Industrial Park, NW England and its buried sewerage network presents a potential source of pollution to the underlying Triassic Sherwood Sandstone aquifer. Weakly permeable superficial deposits beneath the site may provide a barrier to potential pollution of groundwater in the aquifer. The aim of the study was to develop and apply a 3D model of the superficial deposits beneath the park to a qualitative assessment of the vulnerability of the underlying aquifer to potential pollution. The study also aimed to devise a method for the integration of the 3D geological model of the shallow sub-surface with the buried utility network.

The 3D model revealed 8 superficial units. Glacial till, comprising clay and silt, was the only weakly permeable deposit identified. Other deposits were interpreted as permeable. The underground utility network was integrated in 3D with the geological model. Those utilities overlying less than 2.5 m of till were interpreted to represent the most vulnerable parts of the underlying aquifer. The greatest relative vulnerability to the aquifer occurred in the south and south-west of the project area.

The study identified a novel method for the integration of a 3D geological model and a buried sewerage network. The identification of these utilities prioritised the areas of highest relative vulnerability of the Sherwood Sandstone aquifer to potential pollution from utility leakage. This approach enabled the development of a hazard identification and prioritisation scheme for future improvements to the buried sewerage network serving Knowsley Industrial Park.

Keywords: aquifer vulnerability, utilities, 3D modelling, urban environments, Knowsley Industrial Park

1 INTRODUCTION

Knowsley Industrial Park is one of the largest industrial parks in Europe and is located 6 km north-west of Liverpool, UK (Figure 1). The park and the surrounding study area of Kirkby, occupy an area of approximately 17 km^2. Topographically, the area lies between 20 and 45 m OD, with a gentle slope across the project area from east to west.

The site was occupied by a Royal Ordnance Factory from the 1930s to approximately 1960 (Price et al., 2008). The area was subsequently developed as an industrial park. A wide variety of commercial and industrial organisations are now located on the site and a number of authorised processes and activities take place.

The buried utility infrastructure beneath Knowsley Industrial Park may be in a poor condition. There is potential for pollution of groundwater within the underlying Sherwood Sandstone aquifer from historic contamination of land within the estate. The utilities network may provide a pathway for the migration of possible contaminants into the deeper aquifer.

Shallow groundwater, where present, appears to be at a similar level to drains and sewers and in places there appears to be interaction between the shallow groundwater and the drainage system. Shallow groundwater may be polluted in many parts of the estate.

A 3D geological model of superficial deposits allows the distribution, geometry and physical properties of the shallow sub-surface to be identified. Integration of the 3D model with buried utilities data can be used to provide a tool to identify the relative vulnerability of and recharge to the underlying aquifer from potentially leaking utilities. This provides a basis for environmental decision making and the development of a utilities management strategy that can prioritise those utilities that may provide the highest potential hazard to the underlying aquifer if found to discharge poor quality water through leakage.

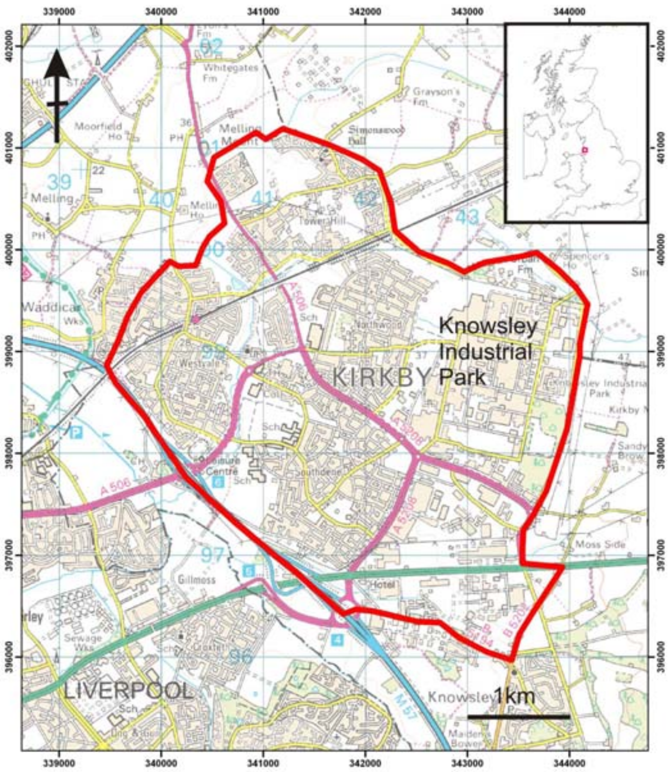

Figure 1. Location map of Knowsley Industrial Park and surrounding project area (shown in red). OS topography © Crown Copyright. All rights reserved. 100017897/2008.

1.1 *Bedrock Geology*

The site is underlain by bedrock of the Sherwood Sandstone Group. It comprises well-sorted, medium-grained, red-brown and orange-yellow sandstone with small-scale, low-angle trough cross-bedding with angular to sub-angular sand grains. Small extraformational rounded quartzite pebbles and mudstone clasts may be present in part. The sandstone has a proven thickness of 300 m in the Pilkington Simonswood (SJ49NW/2) borehole.

1.2 *Superficial Geology*

Much of the study area is covered by extensive spreads of superficial deposits of Quaternary age. These can be divided into three major categories:

- Glacial Deposits (mainly till). Includes coversands (Shirdley Hill Sand Formation), presumed to be mainly of late Devensian age
- Post Glacial Deposits (mainly fluvial). Associated with the development of the headwater streams of local river systems and peat. Holocene in age.
- Artificial Ground. Anthropogenic deposits, recording man's modification of the surface and shallow sub-surface during the last fifty years

Till forms a cover of variable thickness (0-11 m) over most of the study area. During the last phase of the Devensian glaciation large volumes of meltwater were also released. At the close of the Devensian period, cover sands were deposited across much of the Lancashire Plain (Wilson et al., 1981). During the post-glacial (Holocene) period large areas of peat developed on the Lancashire Plain and the modern river systems developed. As sea levels recovered marine deposits were deposited around the edges of the Lancashire Plain.

1.3 *Utilities Distribution*

Utilities beneath the site comprise a network of foul, surface water and combined sewers. The distribution of utilities infrastructure beneath the site is shown in Figure 2. The utilities data was held as 4722 individual segments of variable length between manhole access points. Each end of the utility segment contained an attribute corresponding to its elevation in metres above OD. This attribute provided the elevation data necessary to enable integration and spatial querying in 3D with the 3D geological model.

2 MODELLING METHODOLOGY

A 3D geological model was constructed to enable the distribution, geometry and elevations of all superficial deposits beneath the site to be identified. The elevations corresponding to the base and top of each geological unit could then be queried against the elevations of utility segment. By spatially querying the models, the relative elevations of potentially leaking utilities could be qualitatively assessed against geological units interpreted as weakly permeable.

2.1 3D Geological Modelling

Geological modelling of superficial deposits in the project area was carried out using GSI3D™ modelling software (Kessler et al., 2008). The software and its workflow allow the user to create 3D geological models by combining interpreted digital borehole data, Digital Terrain Models (DTMs), digital geological maps to construct an intersecting grid of cross-sections. From the series of intersecting cross-sections, the surface and sub-surface distribution of each geological deposit is then defined and the geological model is calculated to derive the 3D distribution, geometry and elevation of each geological deposit.

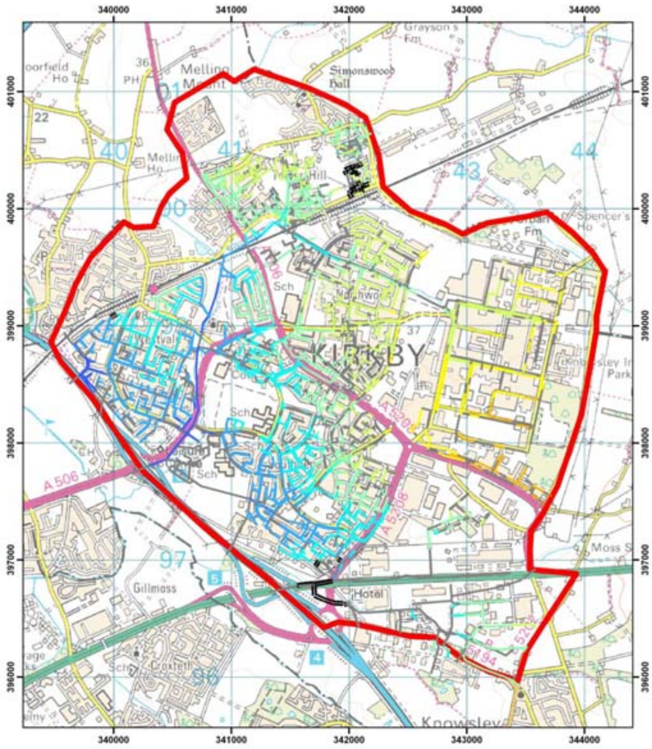

Figure 2. Location and elevation of utilities infrastructure beneath Knowsley Industrial Park and surrounding area (low elevations in blues, higher elevations in orange and red). Utilities locations published with permission of United Utilities. OS topography © Crown Copyright. All rights reserved. 100017897/2008.

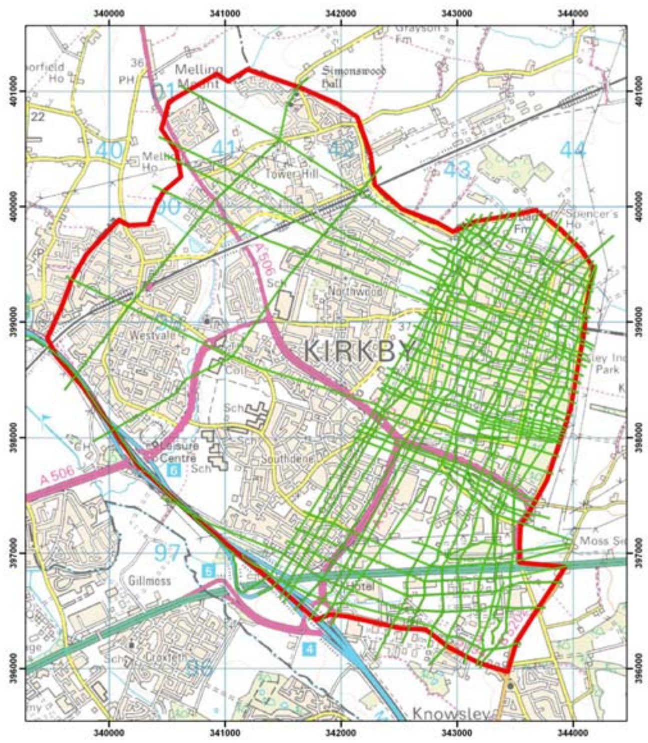

Figure 3. Location of GSI3D™ cross-sections used to construct 3D geological model in Knowsley Industrial Park. OS topography © Crown Copyright. All rights reserved. 100017897/2008.

2.1.1 *Borehole coding, interpretation and uncertainty*

Lithological and lithostratigraphical interpretations of boreholes were derived from scanned paper records held within the National Geoscience Data Centre at the BGS and additional records provided by the Agency. 1279 coded boreholes were available and digitally interpreted and coded.

Most borehole information was clustered in relatively small, dense areas in the eastern parts of the area associated with multiple phases of site investigation within Knowsley Industrial Park. In contrast, the central and western parts of the area have a lower borehole density.

2.1.2 *Cross-section framework and correlation*

58 cross-sections were constructed and geologically correlated within GSI3D™ and their locations are shown in Figure 3. Coded borehole data, digital elevation models, scanned and georegistered map images and digital geological maps were imported and used to define the distribution and geometry of the superficial deposits along the lines of section.

A digital elevation model was required to provide the top layer of the model from which all geological units below are calculated and cross-sections correlated. The Digital Elevation Model used for the 3D modelling was the NEXTMap (Intermap Technologies Inc) 25 m cell size model. Digital, coded boreholes were imported into GSI3D™ from the BGS Borehole Geology database in their correct spatial positions. From the complete database of coded boreholes, the highest quality logs were selected for inclusion in the cross-sections. The selection process was based on a number of key criteria, including depth (preferably boreholes reaching rockhead) and quality of the description.

Cross-sections displaying borehole information were displayed in GSI3D™. Correlation lines were digitised between boreholes corresponding to individual geological units proved within them.

Importantly, each correlation line is made up of a series of nodes with known coordinates and elevations. When all of the cross-sections are combined, the lines and nodes for every geological unit provide the basis for the calculation of the 3D model.

The GSI3D™ methodology provides the flexibility to incorporate the modeller's interpretation where borehole or other data, may be uncertain. For example, where boreholes do not penetrate rockhead, the modeller is able to enhance the 3D model, by using surrounding borehole data or local knowledge, to define the thickness or geometry of the deposit that provides additional information to the minimum level of data provided by the borehole. The resulting 3D model therefore does not rely on borehole data alone.

In general, uncertainty in the thickness and geometry of the modelled geological units is greatest in data poor areas. Confidence is highest in data rich areas. Data rich areas are represented by dense areas of closely spaced boreholes.

2.1.3 *Model calculation and attribution*

The 3D geological model was calculated by interpolating surfaces between correlated units present on cross-sections and envelopes defining the distribution of those units at surface or in the sub-surface. The model is calculated “top-down”, beginning at the ground surface (represented by the Digital Elevation Model). This stack of surfaces forms the 3D geological model from which the top and base elevation and thickness of each geological unit can be calculated and exported. The stacked 3D geological model is shown in Figure 4.

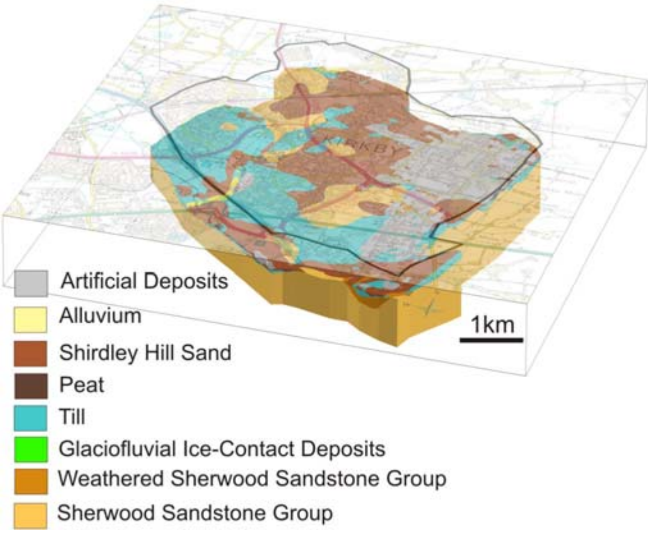

Figure 4. 3D geological model. Vertical exaggeration x10. Ordnance OS topography © Crown Copyright. All rights reserved. 100017897/2008.

Each geological unit was attributed with a lithological, lithostratigraphic and inferred permeability classification of permeable of weakly permeable. The inferred permeability represented the qualitative assessment of inferred permeability based on the lithological composition of each geological unit.

2.2 *Integration of utilities data*

The vulnerability of an aquifer to a source of pollution depends in part on the distribution and thickness of weakly permeable sediments that broadly correspond to those deposits whose primary lithology is either clay-rich or silt-rich (O'Dochartaigh et al., 2005; Lelliott et al., 2006). These sediments or sediment assemblages may reduce the vulnerability of an aquifer to potential pollution by acting to inhibit or reduce lateral or vertical flow towards the aquifer. A qualitative assessment of the vulnerability of an aquifer to potential pollution can therefore be made with reference to the thickness and distribution of weakly permeable superficial deposits overlying the aquifer.

Glacial till represents the only superficial deposit whose primary lithology is either dominantly clay or silt. The composition of the till is variable however. Within the till, clay or silt is present as a matrix with sand and gravel commonly present as lenses or as secondary or tertiary components of the till matrix. For the purposes of this project, till has been attributed as a weakly permeable unit for the qualitative assessment of aquifer vulnerability within Knowsley Industrial Park. Further assessments of the hydrogeological properties of the superficial deposits along with groundwater elevations and flow paths, were beyond the scope of this study.

The extent of the calculated top and base elevations and thickness of till exported from the 3D model of superficial deposits was queried against the positions of surface drains and foul sewers. Utility segments whose invert level (elevation relative to OD) occurs beneath the base of the till were interpreted to lie directly within the Sherwood Sandstone aquifer or permeable sand and gravel dominated superficial deposits. Similarly, pipeline segments that lie beyond the extent of the modelled till deposit are interpreted to lie within the Sherwood Sandstone aquifer or permeable superficial deposits. These utility segments may pose a higher potential hazard to the underlying aquifer than those segments that are separated from the aquifer by till. Utility segments that lie above the top surface of the till or within it, may pose a lower relative hazard from pollution, depending on the thickness of the underlying till beneath them.

Utility segments stored as lines were initially converted to points representing the end points of each segment. The minimum invert elevation (corresponding to maximum depth) was selected and compared against three surfaces derived from the 3D geological model. The surfaces represented the top and base elevation of the till and its thickness.

A spatial query was then designed to identify the relative elevations of the buried utilities to the till surfaces and classified as “Above_Till”, “Below_Till” and “Within_Till”. They are shown in Figure 5.

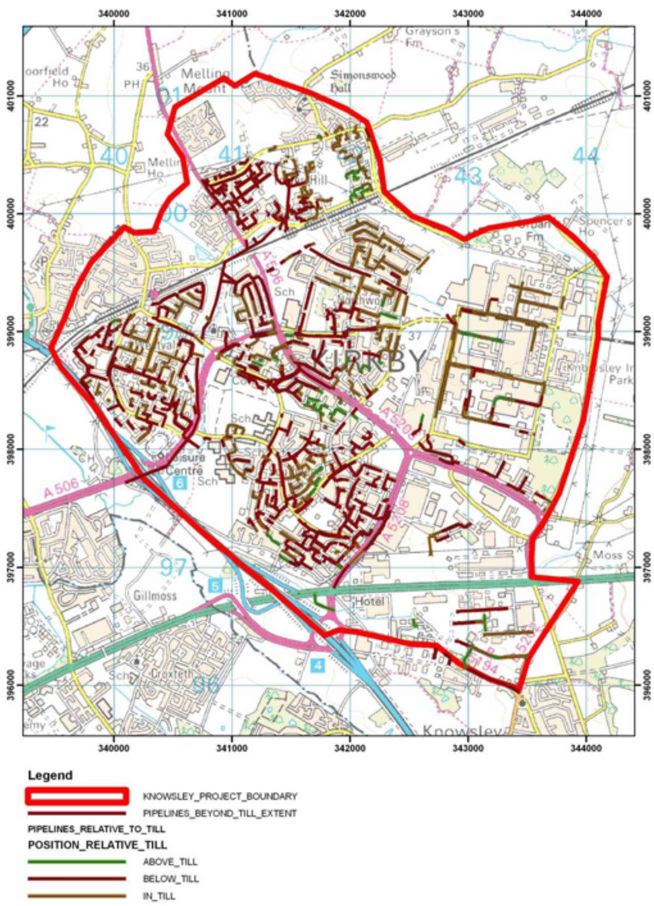

Figure 5. Elevation of utilities relative to till. Utilities locations published with permission of United Utilities. OS topography © Crown Copyright. All rights reserved. 100017897/2008.

3 RESULTS

3.1 *Superficial Geology as reveled by 3D modelling*

A summary of the main superficial units that were identified as a result of 3D modelling is provided in Table 1.

3.1.1 *Weathered Sherwood Sandstone Group*

In addition to the superficial deposits shown in Table 1, the weathered part of the Sherwood Sandstone bedrock was also modelled. In this area the Sherwood Sandstone Group shows a weathering profile from unconsolidated sand to sandstone bedrock. Generally, where concealed by natural superficial deposits, this profile extends to depths of between 1.5 and 3 m. This phenomenon was often considered to be glaciofluvial in origin. However, it is now firmly established that weathering in Permo-Triassic sandstones is commonly preserved below glacial deposits.

	Geological Unit	**Thickness (m)**	**Lithology**	**Environment (inferred)**
Holocene	Made Ground	0-5	Mixed	Anthropogenic (Artificial Deposits)
	Alluvium	0-3	Sand or peaty sand	Fluvial
	Peat	3-5	Peat	Organic
	Shirdley Hill Sand Formation	0-2	Sand	Aeolian
	Buried Peat	0-2	Peat	Organic
Pleistocene (Devensian)	Intra-till lenses	<1->10	Sand and gravel	Sub-glacial and supra-glacial drainage associated with glacial ice
	Till	<7	Gravelly clay with thin interbedded sands and silts	Sub-, supra- and intra-glacial
	Basal glaciofluvial deposits	<9	Sand and gravel	Sub-glacial drainage

Table 1. Superficial Geology as revealed by 3D geological modelling.

3.2 *Aquifer vulnerability and utility hazard prioritisation*

For those pipeline segments that lie above or within till, the degree to which till may prevent vertical migration of potential contaminants to the underlying aquifer is dependant partly on its thickness and weathering state. Where these pipelines overly thin till, the relative potential hazard may be greater than where they overly thick till. It is therefore necessary to assess the elevation of the utilities in relation to the thickness of the till beneath them.

The terms “thick” and “thin” till are relative. Previous studies (Lelliott et al., 2006) have used a thickness value of 5 m to classify till as permeable or weakly permeable. This is because thin till close to the ground surface may be affected by weathering and flow may be enhanced as result of the creation of fractures and fissures. It was beyond the scope of this study to interpret the weathering state of till beneath Knowsley Industrial Park. To provide a qualitative assessment of the relationship between utilities and till thickness, the average thickness of till was calculated as 2.5 m. Thick till is defined as till greater than 2.5 m in thickness and thin till is defined as less than 2.5 m thick.

Of those segments that lie above or within till, 558 overlie greater than 2.5 m of till while 501 overlie less than 2.5 m of till (Figure 6).

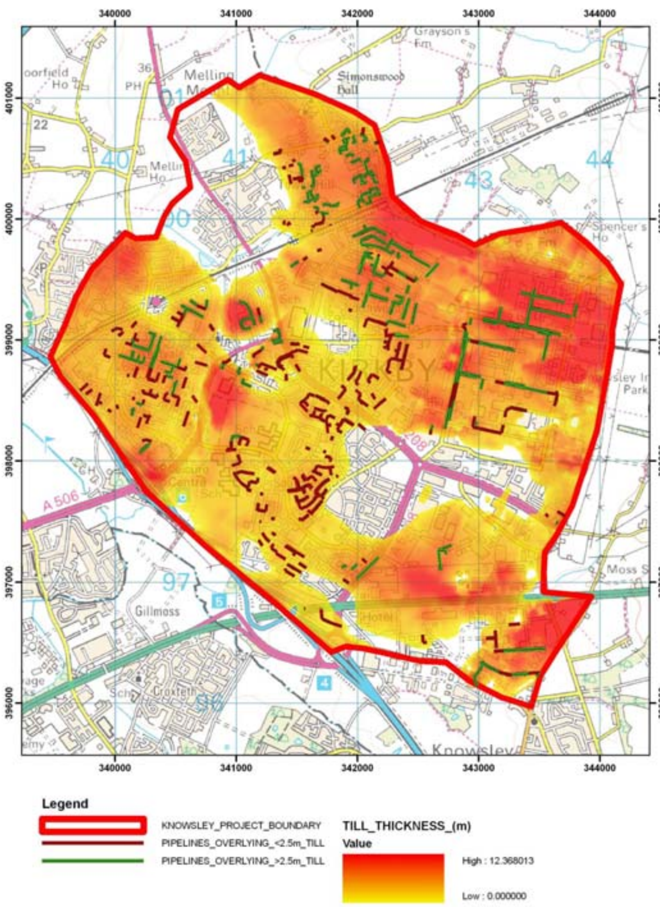

Figure 6. Utilities location and elevation relative to till thickness beneath them. Utilities locations published with permission of United Utilities. OS topography © Crown Copyright. All rights reserved. 100017897/2008.

4 CONCLUSIONS

A 3D geological model can provide a qualitative scientific basis for the identification of the most vulnerable areas of an aquifer subject to potential pollution from historic land uses. In Knowsley Industrial Park the buried utility infrastructure may be in poor condition, resulting in leakage of potentially contaminated effluent from them.

Aquifer vulnerability depends in part on the thickness and distribution of weakly permeable superficial geological material. By modelling weakly deposits in 3D, the resulting surfaces can be intersected with a utilities model in 3D space. This allows the identification of those utilities that pose the highest hazard (and consequently highest relative vulnerability) to the underlying aquifer.

This integrated modelling approach enables environmental decision makers to prioritise those parts of the utility network that pose the greatest risk to the deeper aquifer. The prioritisation scheme can then be used to focus future upgrades to the utilities network within Knowsley Industrial Park.

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