The Development of a GIS methodology to assess the potential for water resource contamination due to new development in the 2012 Olympic Park site, London

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Abstract.

The Initial Screening Tool (IST) has been developed to enable Planners to assess the potential risk to ground and surface water due to remobilisation of contaminants by new developments. The IST is a custom built GIS application that improves upon previous screening tools developed by the British Geological Survey (BGS) through the inclusion of 3-D geological data and an enhanced scoring methodology. The key new feature of the IST is the ability to track individual pollutant linkages, from a source of contamination, along multiple possible Pathways to potentially susceptible Receptors. A rule based approach allows the methodology to be easily updated, and as a result the IST has a role in scenario planning. The application provides output in the form of an automatically generated report, in which details of the potential pollutant linkages identified are presented. The initial research area selected was the Olympic Park site, London.

Introduction.

The United Kingdom's Environmental Protection Act (1990) defines the structure and authority for waste management and the control of emissions into the environment. Contaminated land management in the UK is defined in Part IIA of this act. Part IIA places specific duties on Local Authorities to inspect their areas, to identify contaminated land and to remediate it under a "suitable for use" approach. Furthermore, it provides a system for the identification and remediation of land where either: significant harm is being caused, there is a significant possibility of such harm being caused, significant pollution of the water environment is being caused, or there is a significant possibility of such pollution being caused. As a consequence of this legislation a plethora of site prioritisation tools based on the hazard-pathway-target (receptor) approach have been developed within the UK, e.g. Ander et al. (2003); Department of the Environment (1995), and Gilman (2003).

Local Authorities are not only required to identify and remediate contaminated sites they are also required to rank sites. This has facilitated a more efficient use of staffing and financial resources by targeting highest priority sites first, in a systematic and defensible way. Generally, UK prioritisation tools were based on similar American and Canadian models, such as those described by Canter et al. (1997); they are predominantly qualitative and semi-quantitative. Of these tools, the DRASTIC Index (Aller et al. 1987) has had the biggest impact on the development of contaminated land prioritisation tools in the UK, including the British Geological Survey ConSEPT (**Con**taminated **S**ite **E**valuation and **P**rioritisation **T**ool), which is an integrated GIS tool developed for the prioritisation of potentially contaminated land (Ander et al. 2003).

With the development of attributed 3-D geological modelling at the BGS (Royse et al. 2009), there was an opportunity to take contaminated land prioritisation into the third dimension. This offers the possibility for additional discrimination and prioritisation by the integration of supplementary scenarios, such as: aquifers at depth that may be impacted by the construction of deep foundations (basements or piles) causing contaminant re-mobilisation; the influence of the depth of the unsaturated zone; the relevance of structure and the use of hydrogeological domains (Lelliott et al. 2006; McMillan et al. 2000).

This opportunity was embraced in the context of a British Geological Survey (BGS) 5-year interdisciplinary applied research project. Subsequent to a scoping report which assessed the geological needs of stakeholders in the Thames Gateway (Royse 2005; Royse et al. 2005) a project was established to develop an Initial Screening Tool (IST). The tool’s remit was to assist Planners with the assessment of the potential risk to groundwater and surface waters from contaminants mobilised by redevelopment in the Thames Gateway Development Zone. The objective therefore was to build a 3-D component into a current screening tool, so that an assessment could be made that took into account subsurface as well as surface features. The project’s focus on the Thames Gateway was justified because over 80% of the public water supply is derived from groundwater (Lloyd et al. 1998), thereby making groundwater protection a key issue. When assessing risk to groundwater (Royse et al 2010) 3-D information is crucial. Therefore, a key feature of the IST was its interoperability with the 3-D modelling environment. Following the decision to host the 2012 Olympic Games in London, the Lower Lea valley site was selected for our pilot study area. This selection was made for a number of reasons, including: the existence of: detailed, 3-D geological and hydrogeological models of the area; established working relations with the London Borough of Newham, and the high profile of the Olympic Park site.

Figure 1: IST pilot area

Conceptual understanding of the Olympic Park site.

The Olympic Park site is on the eastern side of the Lower Lea valley, extending from the River Thames in the south to Temple Mills, in the district of Stratford, in the north. The area is around 6 km in length, and just over 2 km wide (Figure 1). The topography of the Lower Lea Valley, is low lying (below 20 m OD) and is underlain by alluvial soils with river terrace deposits (Taplow Gravel and Kempton Park Gravel Formations) forming the higher ground to the east and west. The area lies to the north of the London synclinal axis which influences the distribution of the sub-surface, Palaeogene and Neogene bedrock geology. The older Lambeth Group sediments, which are found in the north of the pilot area, are moving southwards, progressively capped by the Thames Group (London Clay and Harwich Formations). Below the Paleogene and Neogene strata (Figure 2) is the Cretaceous Chalk Group (the primary groundwater aquifer for SE England).

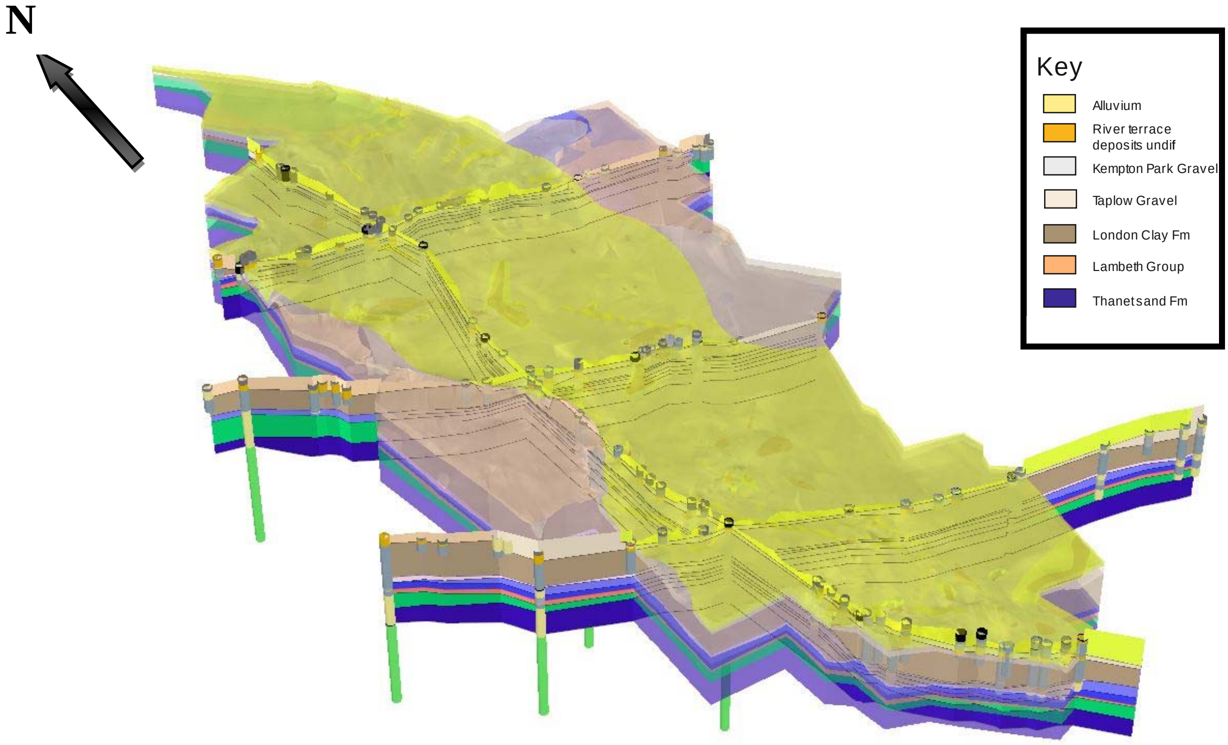

Figure 2: 3-D Geological model of the pilot area.

Artificial deposits of varying thickness and composition cover most of the area, variously classified as: infilled, worked, landscaped and made ground (McMillan and Powell 1999). The types of artificial deposits present in the Lea Valley reflect the industrial history of the area. One legacy of this is several areas of potentially contaminated land. With the Chalk as the major source of potable water and a key Receptor, groundwater protection was integrated as a key component of the IST prioritisation tool.

Summary of earlier GIS approaches to contaminated land prioritisation.

In Part IIA, the definition of contaminated land is based on the existence of a pollutant linkage, which includes: a contaminant Source, a Pathway along which the contaminant can move to a Receptor or target that may be affected, or potentially affected by the contaminant Source. If a contaminant Source is present, but there are no potential effects on a given Receptor, the land is **not** legally “contaminated”. There is therefore no requirement for Local Authorities to look at future scenarios, for example the possibility of developments creating new pathways, which could possibly mobilise confined contaminant sources

The first prioritisation tools developed for Part IIA legislation were spreadsheet hosted. Subsequent developments have incorporated GIS, as typified by Ground View, produced by the National Environmental Technology Centre and ConSEPT, produced by the BGS (Ander et al. 2003). ConSEPT was developed to assist Local Authorities in implementing Part IIA legislation. The aim was to use readily available data to prioritise potentially contaminated sites on the basis of perceived pollutant linkages. The ConSEPT method establishes a pollutant linkage score for three possible Pathways: direct contact (or proximity), surface water, and groundwater and four possible Receptors: humans, controlled waters, ecology and property. Pollutant linkages can then be rationalised as the combinations of Pathways and Receptors that are realistically likely to occur.

The individual Source, Pathway and Receptor scores are derived from a set of evaluation rules, which are processed by a GIS application using a combination of spatial and attribute queries within pre-determined buffer zones. Figure 3 illustrates the nature of queries performed by ConSEPT, showing the identification of a river, well and aquifer within 50m or 250m buffer zones.

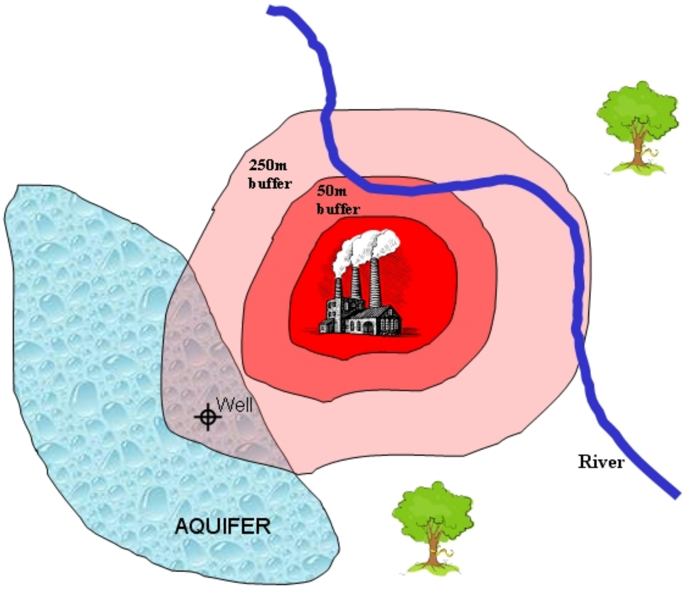

Figure 3: ConSEPT queries: example of a search of rivers, wells and aquifers within 50 and 250 m of the Source site

ConSEPT has been developed for a number of Local Authorities across the UK. It has proved to be a valuable tool for performing a first sift of potentially contaminated sites, with a view to identifying the sites that require more detailed site investigation. However, ConSEPT does have a number of limitations which are summarised below:

- Use of circular buffers: circular buffers can generate false pollutant linkages. Whilst identifying that a Pathway and Receptor fall within a buffer distance of the Source it does not necessarily follow that they will interact to form a pollutant linkage.
- No account is taken of the directions of flow and slope: A river will be identified as a Pathway irrespective of whether it flows to or from a potential Receptor. Additionally, although slope is used as an evaluation factor, the scoring does not take into account whether the slope is towards or away from a potential Receptor**.**
- No account is taken of multiple pollutant linkages: ConSEPT generates a score for each pollutant linkage type (e.g. Source to surface water Pathway to human

Receptor), based on how likely that linkage type is to exist. It does not take into account the number of individual linkages of that type that may be present.

- 3-D data is not used: All data in ConSEPT are 2-D, and where geology data is queried; only the properties of surface are taken into account.

The Initial Screening Tool.

The Initial Screening Tool (IST), was developed to address the limitations identified in the ConSEPT methodology (as outlined above) and to address groundwater and surface water protection issues. The function of the IST is to rank sites that are being considered for future development, based on the identification and scoring of potential pollutant linkages resulting from contaminants mobilised by the proposed redevelopment.

IST Scoring.

As a result of including, 3-D geological, surface water and groundwater datasets, the IST is able to indentify and model individual pollutant Pathways. All potential linkages identified are split into their Source, Pathway and Receptor components, with each component scored via a set of evaluation factors, which build upon those used in ConSEPT. Figure 4 illustrates a typical pollutant linkage identified by the IST. In this case a river acts as a Pathway, potentially transporting contaminants from source to an aquifer (Receptor).

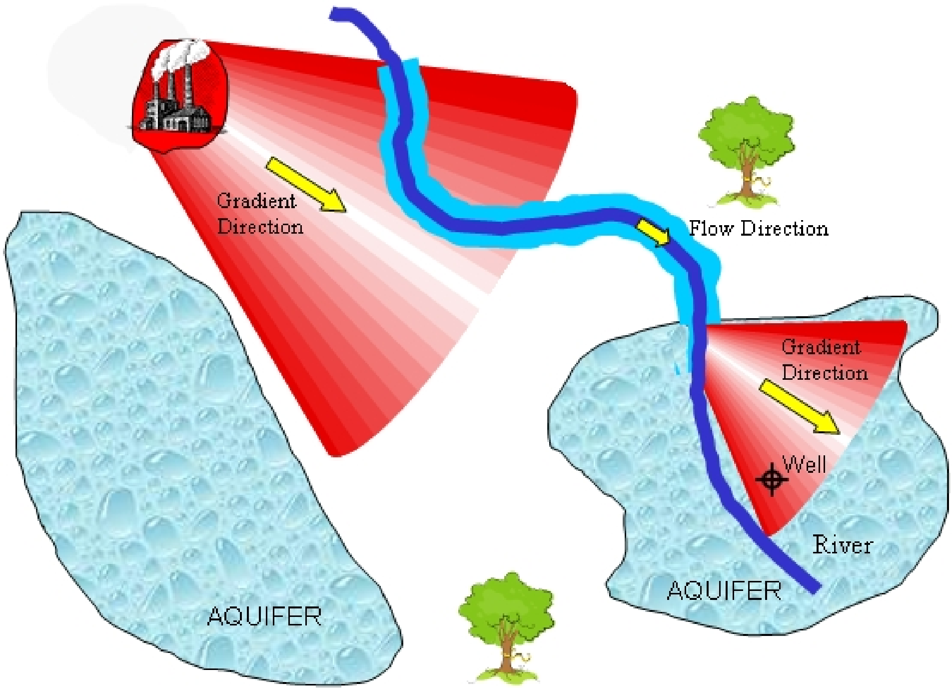

Figure 4: Modelling Pollutant Linkages in the IST

Tables 1 to 5 summarise the evaluation factors implemented by the IST and applied to each identified potential pollutant linkage.

Table 1: IST Source Evaluation Factors.

Evaluation Factor	Description
Contaminant potential	Derived using DEFRA (Table 2.3, Department for Environment Food and Rural Affairs and Environment Agency 2002 b), which lists the contaminants most likely to be found 'in quantities which may be harmful' for given generically classified industries.
Size of site	It is assumed that the larger the area covered by a potentially contaminating activity the greater the scale of the operation, consequently the greater the potential contaminant mass and the greater the potential for harm if Receptors are present.

Table 2: IST Surface Water Pathway Evaluation Factors.

Evaluation Factor	Description
Proximity	Shortest distance from Source site to surface water feature.
Flood potential	Flooding provides a potential agent for the remobilisation and transport of contaminants from a site to a Receptor. This evaluation factor does not quantitatively assess the effect of transport, but highlights that it could take place. The highest scoring Environment Agency flood potential area to intercept the Source feature is used to generate the score.
Topography	The mean magnitude of the gradient of the surface water Pathway along its course towards a Receptor.

Table 3: IST Groundwater Pathway Evaluation Factors.

Evaluation Factor	Description
Proximity	Distance from Source site to groundwater Pathway.
Vulnerability	Model specific hydrogeological domains (e.g. Lelliott et al. 2006).
Surface sealing	An assessment of whether or not the artificial surface of the site prohibits contaminant migration towards the aquifer.
Potentially high permeability features	The possibility that natural or artificial structures passing through any soil, or sediments, forming an unsaturated zone may result in preferential (rapid) flow of contaminants into the aquifer. For example boreholes, water wells and faults.

Low permeability interfaces	The presence of low permeability interfaces in the solid geology in the unsaturated zone, e.g. clay beds in the Lambeth Group can be particularly important in the unsaturated zone both in retaining and retarding contaminant migration. This is derived from the lithological descriptors in the 3-D geological model.
Hydraulic gradient	The slope of the water table in the direction of flow, which influences the rate and direction of contaminant migration. This data is derived from groundwater level data.
Unsaturated zone thickness	Derived from the groundwater level subtracted from the digital terrain model, the unsaturated zone thickness influences the potential for retardation and dispersion of a given contaminant plume.
Proposed foundations	A factor that reflects the potential for the proposed foundation to provide preferential contaminant Pathways, which is based on the proposed foundation type and depth.

Table 4: IST Surface Water Receptor Evaluation Factors.

Evaluation Factor	Description
Proximity	Distance of surface water from Source site.
Surface water classification	Classification of Receptor, i.e. large river, small river, stream, pond etc.

Table 5: IST Groundwater Receptor Evaluation Factors

Evaluation Factor	Description
Proximity	Distance of aquifer from the Source.
Aquifer classification	Principal or secondary aquifer.
Groundwater Receptor classification	Environment Agency Water Abstraction points and Source Protection Zones.

Data collection and creation.

A key issue of the IST project was the availability of the spatial data required to identify pollutant linkages. A number of the datasets included are available at a national scale, for instance boreholes, water wells and groundwater levels (from the BGS), water abstraction sites and source protection zones (from the Environment Agency) and a Digital Terrain Model (from NEXTMap). However, other data included in the IST have been created specifically for the project. In order to model the effect of subsurface geology on groundwater Pathways, the IST includes 3-D geological information highlighting the presence of low permeability features within the vadose zone. This data was extracted in the form of grids of predominantly clay units from the BGS GSI3D 3-D geological model of London (Royse et al. 2009; Royse 2010; Figure 2). GSI3D (Geological surveying and investigation in three dimensions) is a methodology and associated software tool for 3-D geological modelling which enables users to quickly and intuitively construct 3-D solid models of the subsurface for a wide range of applications. In addition, in order to model the potential flow of contaminants via surface water Pathways, a river network was required. This network is processed using the ArcGIS Network Analyst extension to determine which portions of the downstream river network are within a given distance of the Source site. After determining that no such river network was available to the project, an attempt was made to automatically create such a network using a Digital Terrain Model to determine direction of flow. However, this proved difficult within the study area as the region is relatively flat and the required height variation could not be determined from the Digital Terrain Model available. As a result the river network was created manually, starting with a vector dataset of rivers, divided into sections, with each section attributed manually with a direction of flow.

Implementation of the IST in ArcGIS.

The IST was developed within ArcGIS 9.3.1 and relies on the Network Analyst and Spatial Analyst extensions. The code is written in Visual Basic for Applications (VBA) using the editor built into ArcGIS. The IST can be accessed by a button on the toolbar, which opens a floating toolbar providing a set of additional tools that allow the user to zoom to and select a site for scoring.

Once a site is selected, the IST generates scores by searching for potential pollutant linkages that may be acting on the site and then applying the evaluation factors to each linkage found. Searching for pollutant linkages is carried out by generating search areas or Zones of Influence (ZoI) around the Source and then using the geoprocessing operations of ArcGIS to determine any intersection between this Source ZoI and a potential Pathway feature. For each potential Pathway identified, a Pathway ZoI is generated based on the properties of that Pathway, which is used to determine any intersections with possible Receptor features. Each intersection with a Receptor feature then forms a new pollutant linkage.

A novel feature of the search for pollutant linkages is the ability of the IST to model the potential for the surface water to act as a Pathway by following surface water features downstream for a specified distance. This was achieved by using the ESRI Network Analyst extension and the creation of a network dataset. Once the rivers dataset was converted into a network, whereby each link could only be travelled in one direction (i.e. direction of flow), network analysis techniques could be used (similar to those used for road network investigation). This enables the calculation of the proportion of the river network that contaminants can reach over a set distance. The procedure is illustrated in Figure 5, in this example a 1 km section of the river network (shown in red) is examined starting from a specified Source site.

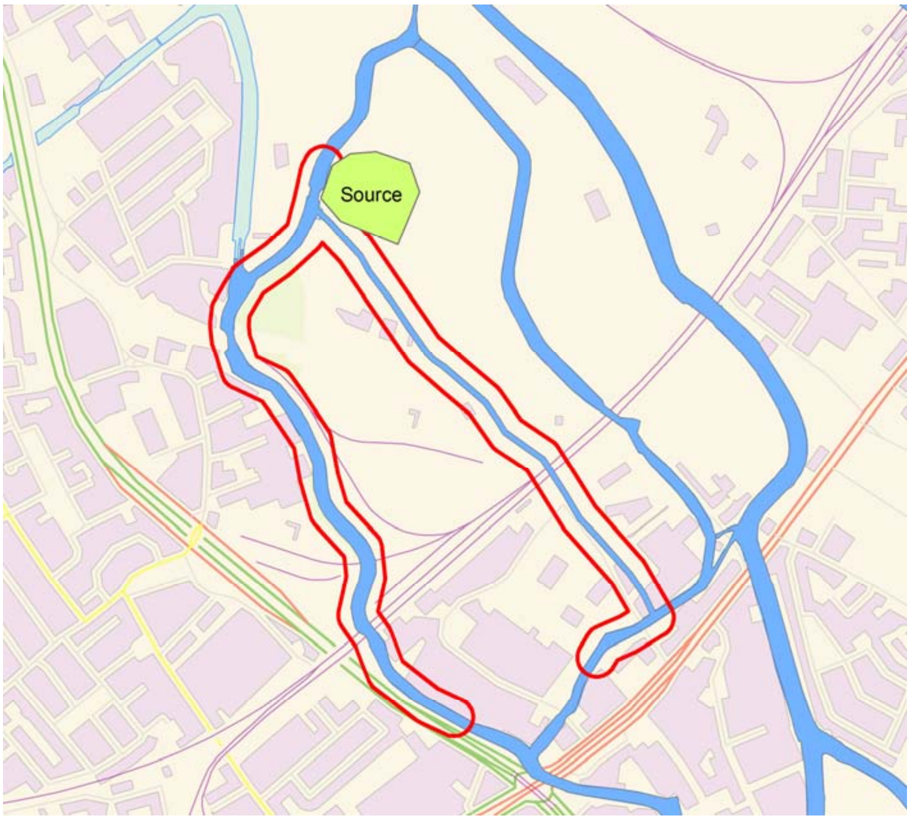

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Figure 5: Deriving the surface water Pathway (red) using network analysis

Another key aspect of the search for pollutant linkages is the technique used for determining pollutant linkage connectivity. The IST has the ability to search for Pathways and Receptors within a directed cone shaped ZoI. The size of each ZoI is based on attributes associated with the pollutant linkage under examination (Ó Dochartaigh et al. 2009). Figure 6 shows a Source ZoI which has been determined in agreement with:

An inner arc radius of the Source ZoI (R_I):

$$R_I = \sqrt{\frac{A}{\pi}} \text{ (where A is the area of the Source site)} \quad (1)$$

An outer arc radius of the Source ZoI (R_O):

$$R_O = 4\, R_I \quad (2)$$

The direction of Source ZoI is down gradient, as calculated from the Digital Terrain Model.

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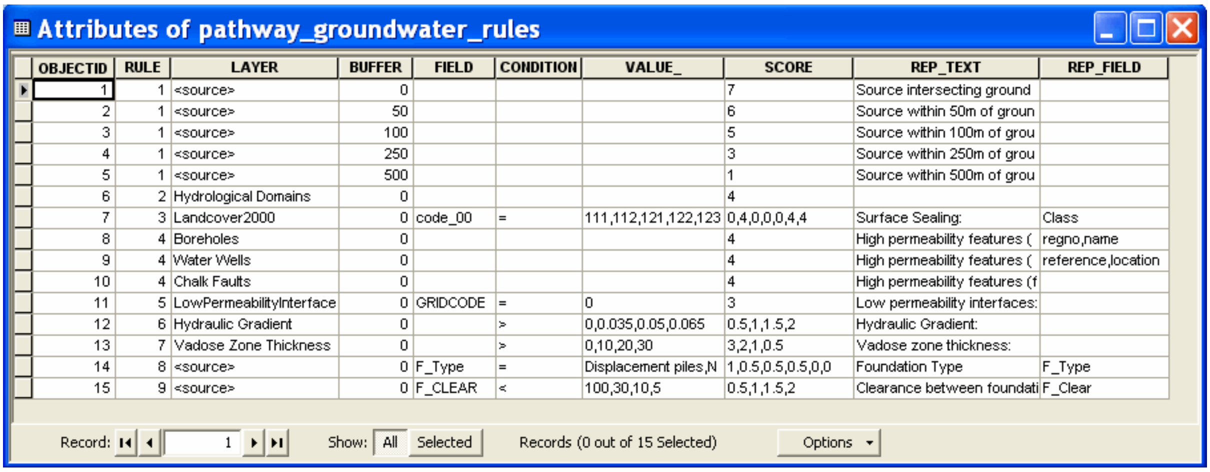
Figure 6: Example of a Source ZoI (red)

Once all potential pollutant linkages have been identified, evaluation factors are applied to generate scores for each linkage. Each evaluation factor is held as a row or rows within standalone tables in an ESRI Personal GeoDatabase (a Microsoft Access database). For example, Figure 7 shows the evaluation factors for groundwater pathway scoring. The key advantage of storing the evaluation factors in this way is that they can be simply accessed by users wishing to test various scenarios, as rules can easily be edited, added or removed using either ArcMap or Microsoft Access.



Attributes of pathway_groundwater_rules

OBJECTID	RULE	LAYER	BUFFER	FIELD	CONDITION	VALUE_	SCORE	REP_TEXT	REP_FIELD
1	1	<source>	0				7	Source intersecting ground	
2	1	<source>	50				6	Source within 50m of groun	
3	1	<source>	100				5	Source within 100m of grou	
4	1	<source>	250				3	Source within 250m of grou	
5	1	<source>	500				1	Source within 500m of grou	
6	2	Hydrological Domains	0				4		
7	3	Landcover2000	0	code_00	=	111,112,121,122,123	0,4,0,0,0,4,4	Surface Sealing:	Class
8	4	Boreholes	0				4	High permeability features (	regno,name
9	4	Water Wells	0				4	High permeability features (	reference,location
10	4	Chalk Faults	0				4	High permeability features (f	
11	5	LowPermeabilityInterface	0	GRIDCODE	=	0	3	Low permeability interfaces:	
12	6	Hydraulic Gradient	0		>	0,0.035,0.05,0.065	0.5,1,1.5,2	Hydraulic Gradient:	
13	7	Vadose Zone Thickness	0		>	0,10,20,30	3,2,1,0.5	Vadose zone thickness:	
14	8	<source>	0	F_Type	=	Displacement piles,N	1,0.5,0.5,0.5,0,0	Foundation Type	F_Type
15	9	<source>	0	F_CLEAR	<	100,30,10,5	0.5,1,1.5,2	Clearance between foundati	F_Clear

Record: 1 Show: All Selected Records (0 out of 15 Selected) Options

Figure 7: Example of IST evaluation factors table held in ESRI Personal GeoDatabase

Once calculated, the final scores are written to the attribute table in the Source site layer, so that sites can be interrogated in the future without the need to rerun the scoring process and in addition, can be symbolised based on the scores they achieve.

On completion of the scoring process, ArcGIS opens an instance of Microsoft Word and populates it with the scores generated, as well as maps showing the individual pollutant linkages and details of the features that form each potential linkage. Communication with Word is carried out using Automation (or OLE Automation) to open a pre-generated template report containing a number of XML-like tags. For example a map tag has the format:

```
<GWmap>layers="OS 10k"</GWmap>
```

The application parses the template, replacing each tag with the relevant map or information.

IST Scoring Walkthrough.

To highlight the components of the IST, this section provides an overview of an example execution of the application. To start, the user selects a Source site; this is achieved by clicking on a feature in a layer of possible sites. At this point a two stage scoring process begins, firstly with attempted identification of pollutant linkages relating to surface water Pathways, and secondly the attempted identification of pollutant linkages relating to groundwater Pathways. In both cases the algorithm initially constructs a Source ZoI (cone) around the Source site (Figure 6). The size of the ZoI is determined by the size of the Source site and the direction of the cone is controlled by the slope direction as derived from the Digital Terrain Model.

During the first stage of identifying surface water Pathways (Figure 8), each portion of the river network that intersects the Source ZoI cone results in the identification of a potential pollutant linkage based on the surface water feature forming both Pathway and Receptor. In addition a surface water Pathway ZoI is constructed. This is achieved by using the Network Analysis functionality to follow the river network a given distance downstream. The distance of the river network that is traversed is based on the properties of the river. At this point a new search is carried out for intersections between any of the surface water Pathway ZoIs and features from the aquifers layer. If an intersection is found, a potential pollutant linkage has been identified to a groundwater Receptor and a Receptor ZoI cone is generated. The size of the ZoI is based on the area of the intersection and the ZoI cone direction follows the groundwater gradient. Finally, each potential pollutant linkage identified is added to the pollutant linkage register to be scored at a later stage.

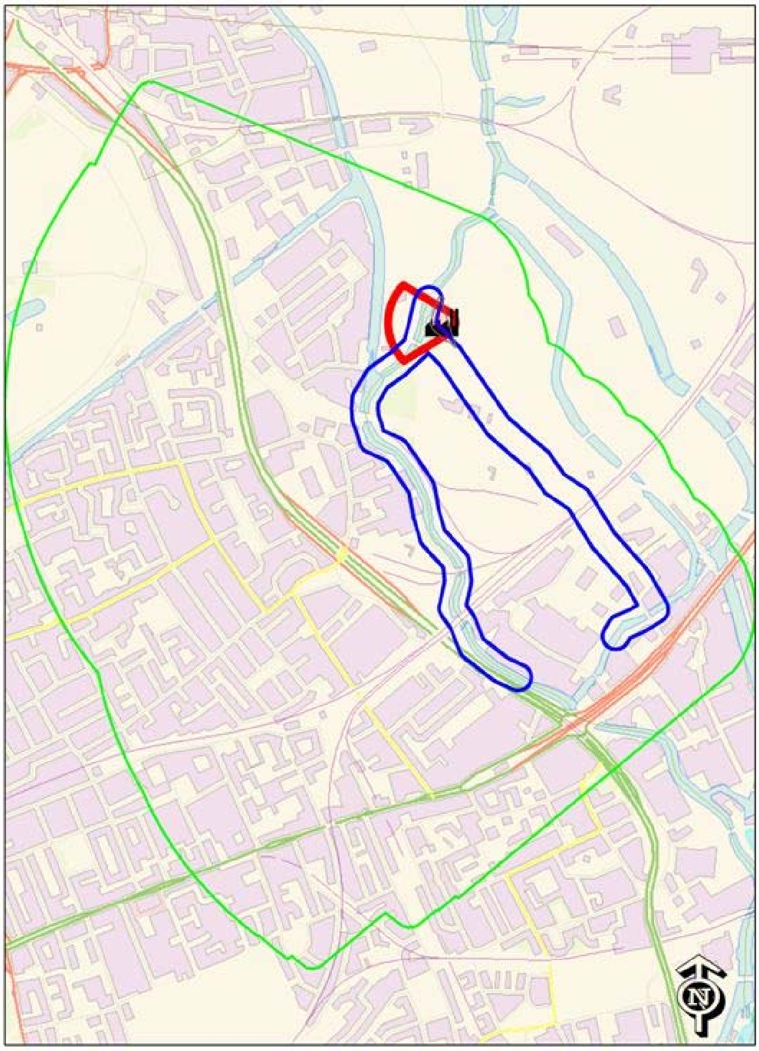


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Figure 8: Surface water pollutant linkages, comprising a Source ZoI (red), surface water Pathway ZoI (blue) and Receptor ZoI (green).

During the second stage of identifying groundwater Pathways (Figure 9), the IST searches for intersections between the Source ZoI cone and the aquifers layer. If an intersection is found, this results in the identification of a potential pollutant linkage based on the groundwater feature forming both Pathway and Receptor. Additionally a Receptor ZoI cone is created. The size of the Receptor ZoI is based on the area of the intersection and the ZoI cone direction follows the groundwater gradient. At this point a new search is carried out for intersections between the groundwater Pathway ZoI and features from the surface water layer. If an intersection is found, a potential pollutant linkage has been identified to a surface water Receptor. As before, each potential pollutant linkage identified is added to the pollutant linkage register to be scored at a later stage.

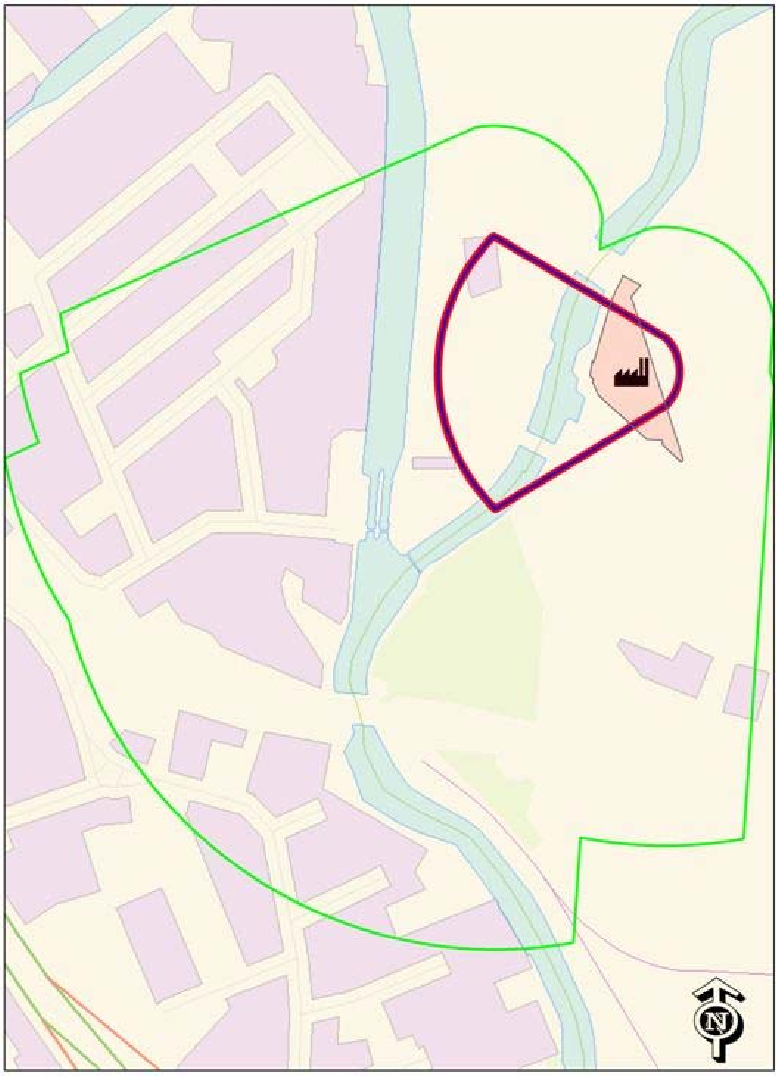

Figure 9: Groundwater pollutant linkages, comprising a Source ZoI (red), groundwater Pathway ZoI (blue) and Receptor ZoI (green).

Once the pollutant linkage register is fully populated, a score is applied to each linkage by applying the relevant evaluation factors (Tables 1 to 5). Current legislation requires that all three components (Source, Pathway and Receptor) must be present for a piece of land to be classified as contaminated. Therefore the IST's overall score for each linkage is taken as the lowest of the three component scores. Each individual pollutant linkage score is then summed to give the total score for the chosen Source site. The output report (generated in Microsoft Word) contains all the documentation of the scoring process, as well as maps highlighting the linkages and full details of the score achieved by each evaluation factor.

Discussion.

The IST was developed to assist planners in the assessment of the potential risk to groundwater and surface waters from contaminants mobilised by redevelopment, particularly in urban environments. Through GIS techniques such as network analysis, generation of zones of influence and geoprocessing, the IST has built on previous contaminated land screening tools by identifying, mapping and scoring individual potential pollutant linkages. This capability and the ability to identify how many potential pollutant linkages are present, is unique.

Generally, tools of this type use circular buffers to identify Pathways or Receptors of interest within a given distance; with no regard for how these features interact. The IST however, is able to scrutinize the connectivity by generating cone shaped ZoIs and attributing features with directions of flow. For example, in order to detect Pathways, the IST creates a cone around a Source site, where the cone's size is determined relative to the size of the Source site and oriented in the direction of slope away from the Source. Additionally, to provide connectivity between Pathways and Receptors, every surface water feature and aquifer is allocated a flow direction, so that potential contaminant migration is modelled only in the direction of flow.

3-D geological and hydrogeological models have been developed by the BGS as part of the London and Thames Gateway project (Royse et al. 2009; Royse 2010; Figure 2). Surfaces were extracted at given depths and incorporated into the IST to allow for a more detailed analysis of the underlying geology. For example, the 3-D model can be used in the identification of low permeability interfaces; the IST is then able to consider successive formations with depth. It should be born in mind that, whilst the IST integrates the 3-D data through interrogation, the 3-D geological model has not been completely integrated. For example the ZoIs are only generated in 2-D. It is possible that in an area containing: a more varied topography; interbedded strata, and a groundwater aquifer that dips beneath a surface water course without hydraulic connectivity, the current version of the IST might unrealistically assume a connection. This is a current focus for tool development, and a future where the IST works totally within a 3-D platform is envisaged.

A key requirement for the ArcGIS IST application was to make the tool simple to use and suitable for scenario planning. As a result, all rules and evaluation factors are held in Microsoft Access tables, making them straightforward to view and to edit. This gives the user the opportunity to investigate the effects of adding, removing or altering rules on the eventual outcome. Additionally, in order to provide comprehensive feedback to the user on the results of the scoring process, the output is presented in an automatically generated Microsoft Word report.

One of the key, and unforeseen, challenges in implementing the IST was managing the communication between scientists and GIS staff. Due to the increased complexity of the surface water and groundwater Pathways as a result of the inclusion of 3-D geological and hydrogeological data, common misunderstandings occurred regarding the level of detail that could be modelled in the GIS, in particular in the subsurface, given the availability of data. As a result, several iterations were required before the implemented rules matched the scientists' vision.

The IST is a valuable tool for assessing the potential risk to water from remobilised contaminants in the Lower Lea Valley. However, there are limitations to this site as a pilot area. Firstly the area contains a single river system (River Lea), underlain by a single chalk aquifer, which limits the opportunity to demonstrate the full potential of the IST to identify multiple pollutant linkages. Applying the IST to other sites is possible, but relies on the availability of 3-D geological modelling (which is not currently available for all areas within the UK). A further area for development for the IST would be to adapt the tool to address aspects of European legislation, for example Integrated Pollution Prevention and Control (Directive 96/61/EC), or the Water Framework Directive (2000/60/EC). In the context of the former, consideration could be given to atmospheric contaminant flow paths and for the latter the IST methodology could provide a tool to assist in River Basin Management planning.

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