SUBURBANISATION OF IMPORTANT AQUIFERS IN ENGLAND AND WALES: ESTIMATING ITS CURRENT EXTENT

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ABSTRACT

The UK rate of conversion of rural into suburban land cover will increase as the UK population is projected to rise towards 70 million by 2056, household size continues to decline and previously-developed land becomes scarcer and less attractive. The resultant change in landuse will significantly impact underlying groundwater resources. GIS analysis is used to estimate the current extent of suburbanised land cover overlying locally and nationally important aquifers in England and Wales. The effect on groundwater catchments will be marked in southern, central and eastern England, where high groundwater dependence and intense pressure for new housing will inevitably lead to a rise in suburban land cover on periurban catchments that are currently rural land. Water resource planning implications would be better understood with more catchment-scale research. Meanwhile areas of aquifer most likely to urbanise by 2050 and public supplies most vulnerable to the consequent changes need identifying.

Key words: British aquifers, groundwater, public water supply, urbanisation, suburban land use, housing development.

INTRODUCTION- URBANISATION PRESSURES AND GROUNDWATER

The UK is amongst the four most densely populated of the 27 EU states. Its 54% population rise during the 20th century from 38.2 million in 1901 to 59 million in 2001 (1) has naturally been accompanied by extensive urbanisation. This growth continues and at current projections the UK population is conservatively predicted to rise from the present 60.8 million (2006) to 66 million by 2026 and 69.6 million by 2056 (2). As almost 90% of the UK's inhabitants reside in England and Wales (where the population density compared to other EU states is second only to the Netherlands and Malta)(3,4), most population increase will take place there (Figure 1).

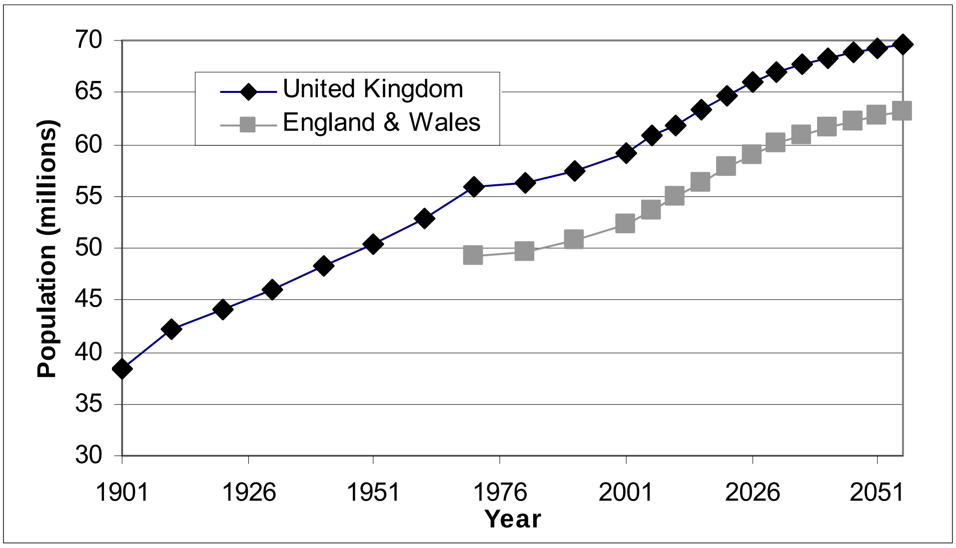

Figure 1 Population trends in the United Kingdom and England and Wales, including projections 2006-2056 (Sources ONS 2006, EPSRC 2007, Government Actuary 2007)

The nature of urbanisation in England and Wales that accompanies these population trends changed radically post-1950 in response to two sets of factors:

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- Economic trends: the decline of mining, fishing and both heavy and light manufacturing in favour of the service sector. Commercial, distribution and retailing development has in some cases supplanted primary and secondary industry on pre-developed land (former factory/industrial sites for example), but in other cases logistics and market factors have led to extensive urbanisation of former agricultural land on periurban fringes. The results are land use changes as widespread as those brought about by industrialisation during the 19th and early 20th centuries. This economic transformation has seen southern, eastern and central England become the most economically prosperous parts of the country. However, the resulting inward migration has seen these regions experience growing urbanisation pressure, so that, for instance, 26% of the UK population now lives in London and the South East even though these two regions cover less than a tenth of the UK's land area (3).
- Social trends: the average household size in England has progressively declined from about 4.5 persons in 1901 to less than 2.4 persons in 2001. It is expected to decline further, in response to various social trends, from the present 2.3 to 2.1 persons by 2026 (2, 5, 6, 7) (Figure 2).

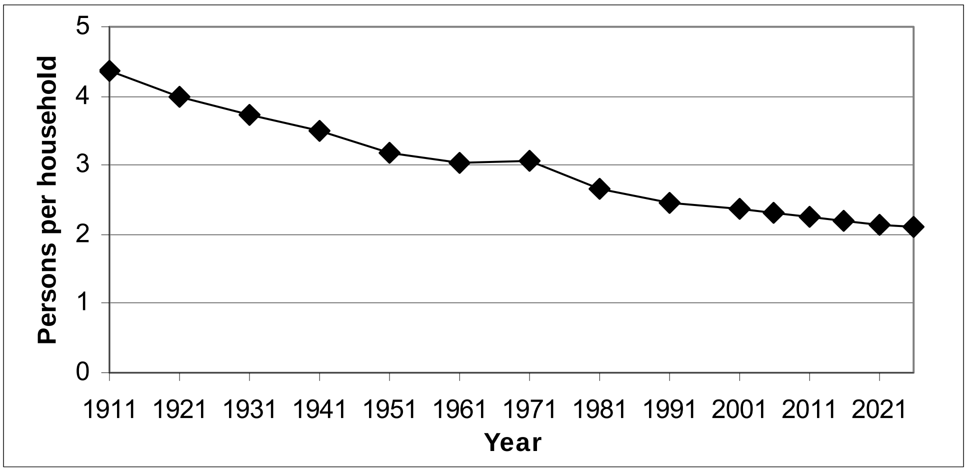

Figure 2 Observed and projected decline in average household size, England and Wales (Sources: Government Actuary 2007, Holmans 2006, Nixon 1970)

An inevitable outcome is increased demand for additional housing. A DEFRA-study, commissioned to assess the environmental impact of increases in the supply of housing in the UK (8), estimates that a further 2.24 million dwellings will be completed just in England alone during the 15-year period 2001-2016. This figure is based on current completion rates and growth areas provision under the Communities Plan (9)[1]. This is equivalent to about 150,000 dwellings/annum and the estimated landtake for this residential urbanisation alone would be 785 km^2 (8), about 60% of which will be on previously undeveloped ('green field') sites. (Table 1).Table 1 New housing construction and corresponding land requirements 2001-2016, based on past completion rates 1996-2001 plus Communities Plan provision (Source DEFRA 2004)

Indicator	**England (all regions)**	**Southern, Central and Eastern England***
No.of dwellings		
Previously developed land ('Brown Field')	1,280,420	938,672
Green Field	963,675	710,104
Totals	**2,244,095**	**1,648,775 (73.5%)**
Anticipated land take (km^2)		
Previously developed land	310.5	225.1

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[1] The 2003 Communities Plan (Sustainable Communities: Building for the future) includes amongst its aims a long-term programme of action for delivering sustainable communities in both urban and rural areas, including tackling housing supply issues in the South East.

('Brown Field')		
Green Field	475.0	348.2
Totals	**785.5**	**573.3 (73%)**

*Includes East and West Midlands, East of England, London, South East and South West Regions

Other reports (3,6) note that about 60% of the projected household growth to 2026 will be in London and the East, South East, and South West Regions. Scenarios in the DEFRA report that take into account an increased supply of new housing, to meet projected shortfalls in demand, suggest that the completions and corresponding land take requirements could be up to 4.52 million dwellings and 1479 km² respectively .

While other factors will affect the extent of development at particular locations, there is no doubt that Britain during this century will face a significant increase in the rate of urbanisation, a large proportion of which will be for housing and associated infrastructure located to the south of a line approximately joining the Humber and the Severn.

It is precisely this area where groundwater resources play a major water supply role. This may be either as productive, regionally important aquifers such as the Chalk, the Permo-Triassic Sandstones or the Lower Greensand that support major public water supply abstractions, or in local aquifers, tapped both by private users and smaller but strategically important public supplies. Aquifers underlie over 55% of the land area of England and Wales, with groundwater providing 30-80% of public water supply in southern, central and eastern England (10) and probably more than 95% of private supplies nationally (Table 2).

Table 2 Dependence on groundwater for potable supply, England and Wales (DETR, 1997)

Environment Agency Region	**% of total public water supply derived from groundwater**	**% of all licensed groundwater abstraction used for public supply**
Southern	80	87
Anglian	42	71
Thames	34	90
Midlands	40	86
South West	33	91
North West	14	66
North East	14	73
Welsh	8	80
(1) Total groundwater abstracted for public water supply in England and Wales (1997): 5508 Ml/d (32% of total national supply)		
(2) There are no corresponding figures published for private abstractions, but at least 95% of all private potable water supply abstraction is estimated to use groundwater		

Most of these functioning supplies draw from pumping stations located in rural or periurban areas. This reflects in part a long operational tradition of preference for predominantly agricultural groundwater catchments and in part a catchment protection reality. Unlike some European countries such as Germany and the Netherlands, UK water companies do not own or have direct control over their aquifer catchments and so can exert only limited influence over the activities on such land. In such circumstances voluntary agreements and regulatory procedures are more easily undertaken in rural areas where only a few landowners are involved. This pragmatic but somewhat vulnerable situation is likely to change over the coming decades as suburbanisation increasingly encroaches upon presently rural periurban groundwater catchments.

This paper surveys the extent of urban areas relative to productive aquifers in England and Wales, assesses the likely proportion of suburbanisation, and comments on the potential impact of the continued expansion of this distinctive land use over the next 50 years.

METHODOLOGY

For the assessment, GIS analysis was employed to compare spatial datasets, Currently available datasets were used throughout and are listed in Table 3

Table 3 Datasets used for GIS analysis

Data Type & nominal scale	Date of dataset	Source	Notes
Hydrogeology (1:625,000)	1977	British Geological Survey	Digitised 2004
Built areas (1:250,000)	2002	Ordnance Survey	Strategi® licensed dataset
Postcode areas	2002	Ordnance Survey	Code-Point® licensed dataset
Topography (1:50 000)*	2002	Ordnance Survey	Colour raster converted to black & white
Superficial deposit thickness*	2004	British Geological Survey	Basic Superficial Thickness Model (BSTM), generated by direct modelling; 50 m grid.

* Used for illustrative purposes and not for spatial analysis in this paper

The data analysis procedure is shown schematically in Figure 3 and comprised 4 stages:

1. Creation of a thematic layer comprising all land areas with potentially vulnerable bedrock or superficial aquifer at the surface,
2. Re-classification of the built areas dataset to separate rural and urbanised environments,
3. Division of the urbanised dataset into suburban and other urban land uses,
4. Overlay of derived maps on aquifers to produce area statistics.

1. Creation of aquifers layer

The bedrock hydrogeology dataset was derived from the 1:625,000 hydrogeology map (11). This dataset classifies bedrock either as an aquifer or as impermeable and without groundwater (except at shallow depth). The aquifer class is further characterised into those which are extensive and highly productive and those of more limited potential (the least-used of these were excluded), and also whether flow is dominantly via fractures or intergranular. Quaternary deposits overlie bedrock in many parts of England and Wales and the two principal superficial aquifers of this cover were similarly derived. Together these datasets account for the 6 possible subsurface conditions for a given land use (Table 4)

Table 4 Selection of the aquifers thematic layer.

Groundwater setting	Subsurface condition	Status
Land use underlain by aquifer	Bedrock aquifer at outcrop	✓
	Superficial aquifer overlying bedrock aquifer	✓
	Superficial aquifer overlying bedrock non-aquifer	✓
Land use underlain by non-aquifer	Superficial non-aquifer at outcrop overlying bedrock aquifer	✓
	Bedrock non-aquifer at outcrop	✗
	Superficial non-aquifer at outcrop overlying bedrock non-aquifer	✗

✓ , ✗ Included, Not included in aquifers thematic layer

Figure 3 Flowchart of spatial analysis procedure

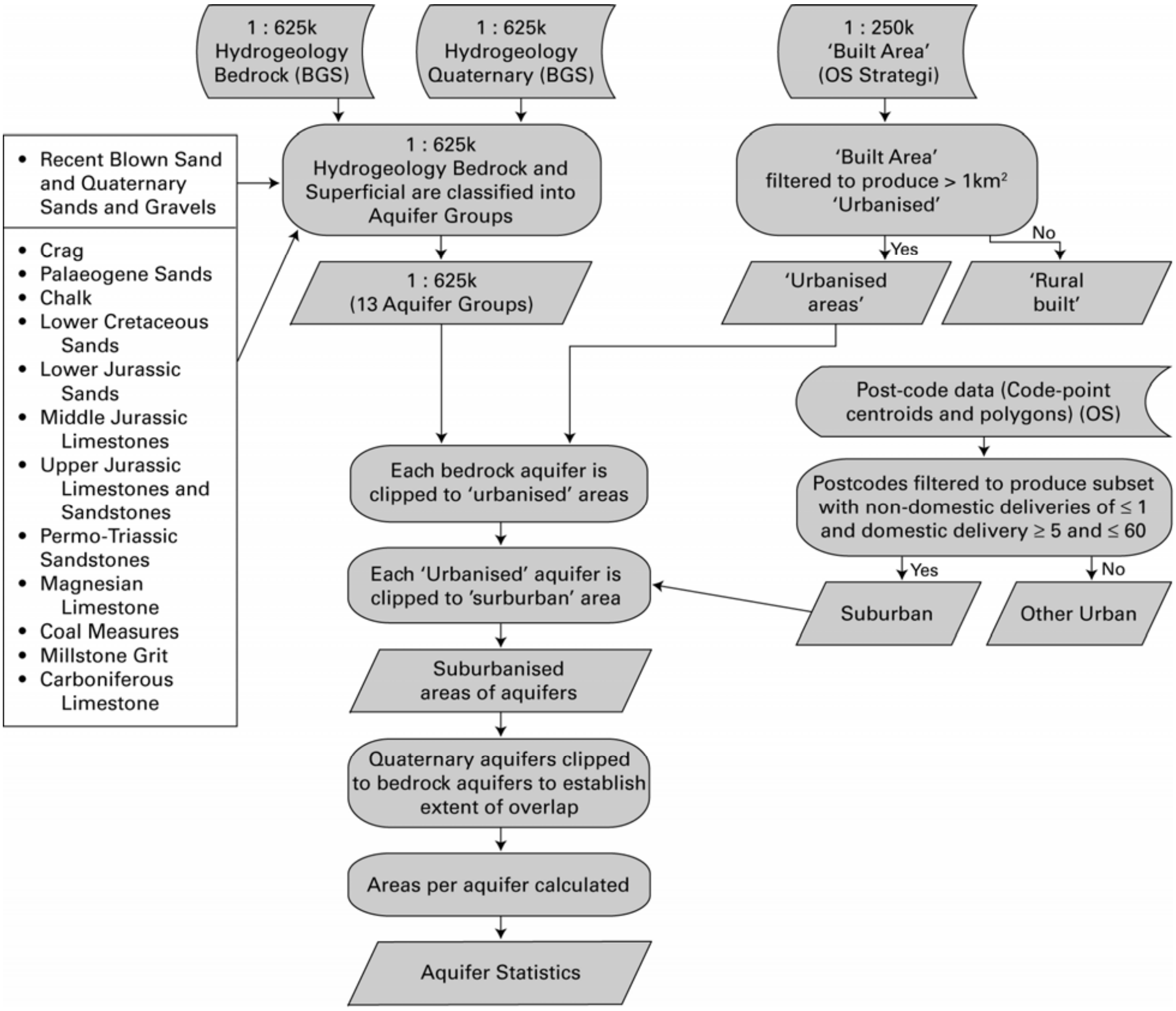
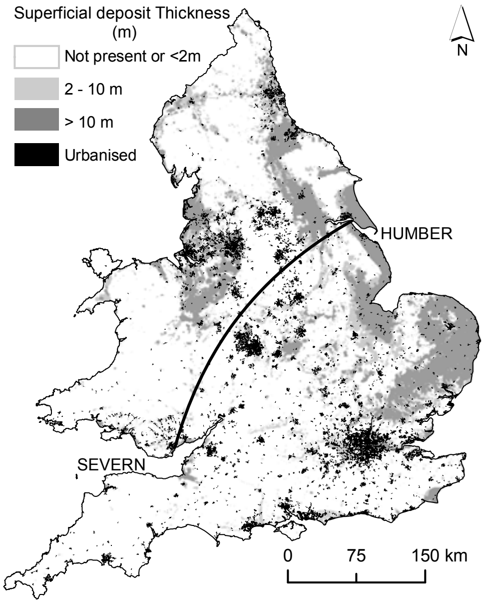


Figure 4 Superficial deposit thickness, England & Wales (modified from Garcia-Bajo & Lawley, 2004)



The aquifers dataset used for analysis purposes in this paper comprises the three classes where land is directly underlain by a bedrock or superficial deposit aquifer plus the subsurface condition where a Quaternary non-aquifer deposit lies upon a bedrock aquifer (Table 4).

The precautionary inclusion of this last-named category was considered justifiable on the grounds of likely aquifer vulnerability but it requires explanation. In the absence of a national map showing the thickness of low permeability strata, Quaternary superficial deposits had to be categorised as aquifer or non-aquifer on the basis of the simplified lithological description of the layer at the ground surface; no account could be taken of actual thicknesses of low permeability strata, nor of vertical variability. So the superficial non-aquifer class as a whole includes, for example, areas where the layer is only a few metres thick (e.g. veneers of glacial till or Clay-with-flints) or is thick but not predominantly low permeability (e.g thin alluvium overlying river terrace gravels).

To inform the decision whether to include this subsurface condition, an experimental version of a superficial deposit thickness map produced by the BGS (12) was compared with urbanised areas (Figure 4). This indicated that many of the deposits that would underlie urbanised areas in southern Britain have thicknesses of 10 m or less. These strata would include both permeable and poorly permeable strata, and it was considered that the protective ability of such superficial deposits is debatable given that many elements of modern urban infrastructure (foundations, basements, cuttings, pipelines etc) would penetrate to at least this depth. The principal area where the approach may be over-precautionary is in the Manchester and South Lancashire/North Cheshire area.

The principal bedrock and superficial aquifers included in the resultant Aquifers Dataset are listed in Table 5 and their outcrop illustrated in Figures 5 and 6.

Table 5 Aquifers Dataset; locally and nationally important aquifers in England and Wales[2]

	Aquifer/ Aquifer Group	**Principal aquifers in group**	**Status**	**Flow type**
Superficial	Recent: Blown Sand	Coastal dunes	LI	I
	Quaternary sands & gravels	Glacial, fluvioglacial and river terrace deposits including Thames, Trent and Yazor Gravels	LI	I
Solid (bedrock)	Crag	Norwich, Red and Coralline Crag	LI	I
	Palaeogene Sands	Oligocene & Eocene sands in Bracklesham Thames and Lambeth Groups, including Bagshot, Reading and Upnor Formations	LI	I
	Chalk	Upper, Middle, Lower Chalk	EHP	F
	Lower Cretaceous Sands	Upper and Lower Greensand, Tunbridge Wells Sands, Ashdown Formation, Carstone, Sandringham Sands, Spilsby Sandstone	EHP, LI	I
	Upper Jurassic limestones and sandstones	Purbeck, Portland Formations, Corallian Group	LI	F
	Middle Jurassic limestones	Cornbrash, Great Oolite, Fullers Earth Rock, Inferior Oolite, Lincolnshire Limestone	EHP, LI	F
	Lower Jurassic Sands	Bridport, Midford, Yeovil and Cotteswold Sands	LI	I
	Permo-Triassic Sandstones	Sherwood Sandstone, Otter and Penrith Sandstones	EHP, LI	I
	Magnesian Limestone	Magnesian Limestone	EHP	F
	Coal Measures	Upper, Middle and Lower Coal Measures, Pennant Sandstone	LI	F
	Millstone Grit	Namurian sandstones and grits	LI	F
	Carboniferous Limestone	Dinantian limestones, Scremerston Group, Fell Sandstone, Basal Conglomerate, Yoredale Series	LI	F

LI	Locally important aquifers	EHP	extensive & highly productive aquifer systems
I	Dominantly intergranular flow	F	Dominantly fracture flow

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[2] The aquifer names referred to in this paper are those typically employed in the British water industry. For more stratigraphically precise descriptions see Allen et al 1997(13), Jones et al 2000 (14).

Figure 5 Bedrock aquifers in England and Wales

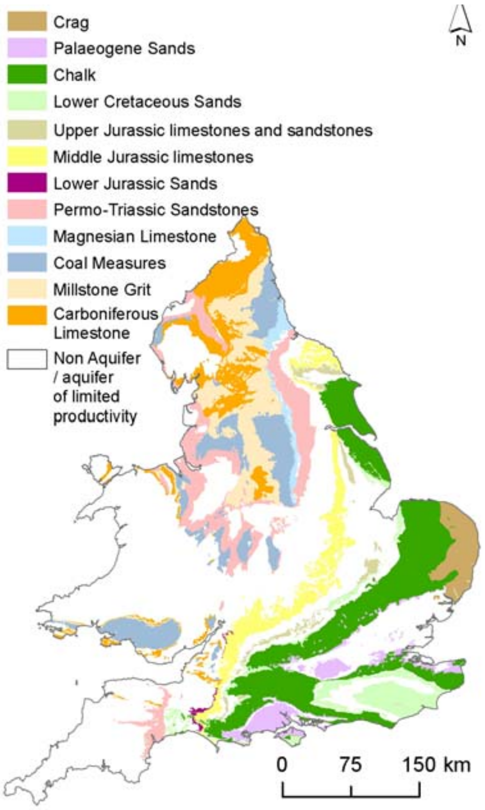
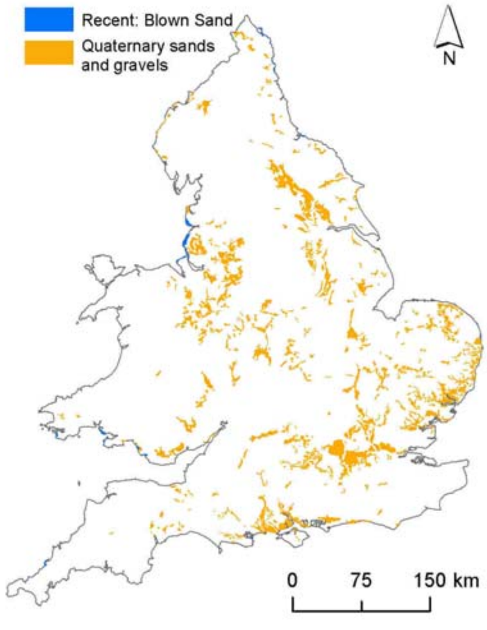


Figure 6 Superficial aquifers in England and Wales



2. Re-classification of the built areas

The base information for built areas was the ‘urban region’ theme of the Ordnance Survey Strategi® dataset. Comparison with sample built areas indicated that this 1:250,000 vector dataset provided a more accurate representation of built areas than others currently available. The dataset has national coverage although for this purpose only that for England and Wales was used (Figure 7). To create an ‘urbanised’ layer the data were queried to select all areas that were over 1km². These then became the Urbanised Dataset. The rest (villages etc, called “rural built” in this paper) were considered too rural to include in further analysis. Both classes are illustrated in Figure 8.

Figure 7 Built areas in England and Wales (source OS Strategi® 2002)

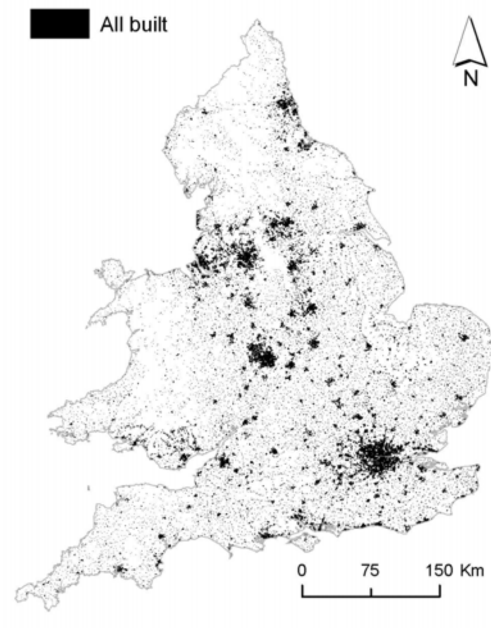
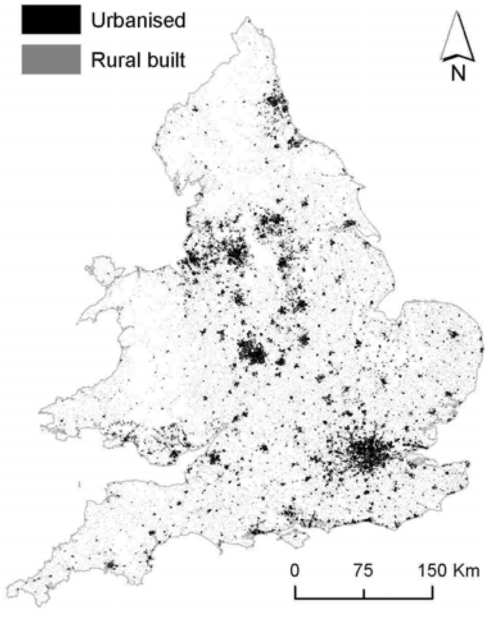


Figure 8 Urbanised and rural built areas in England and Wales



3. *Subdividing urbanised areas.*

The urbanised areas delimited in Strategi® are not subdivided into industrial, commercial or different residential land uses. Some subdivision is, however, required because these urban land use classes have very different water use, recharge potential and contaminant load characteristics. The Ordnance Survey Code-Point® postcode data product provides a means to separate off the relatively benign suburban environment (in groundwater impact terms) as it provides National Grid coordinates for each unit postcode in Great Britain, which can be joined to the corresponding postcode polygons. Used together with Strategi®, Code-Point® has enabled subdivision of the urbanised areas into suburban and 'other urban' classes.

Code-Point® contains fields with data relating to approximately 26 million postal delivery points (15). It uses postcodes that uniquely identify blocks of about 15 addresses, although there is in practice quite a wide range in the number of delivery points in a given postcode, a feature which can be used to infer the nature of the urban land use. The procedure involved filtering Code-Point® on the following query: non-domestic delivery of ≤1 and domestic deliveries ≥5 and ≤60. The twin criteria proved effective for a first-pass screening, the non-domestic criterion screening out industrial/commercial districts and the domestic criteria filtering out both periurban semi-rural development and many dense inner urban residential districts.

4. Overlay on aquifers, accounting for superficial aquifers

The Strategi® and Code-Point® derived thematic layers were then applied to the Aquifers dataset by running a series of spatial queries on the loaded Code-Point® polygons that would select all the postcode polygons that intersect with each of the 13 bedrock and superficial aquifer groups listed in Table 5. This provided 13 shapefiles of all the postcodes overlying each aquifer.

An example of this procedure is illustrated for the Chalk aquifer beneath Luton and Dunstable (Figures 9 and 10), in which the diagrams show the following sequence:

Figure 9:

A. The Chalk outcrop.

B. The built area underlain by Chalk, separated into urbanised and rural built categories.

C. All the postcodes that intersect with the urbanised area where it overlies the Chalk aquifer. The complexity of the postcode polygons that are present in any urbanised area is also demonstrated.

Figure 10:

D. The urbanised area divided into suburban and other urban.

Validation exercises showed that a further stage was required because some postcodes on the outer edge of suburban districts subsume neighbouring rural land/addresses (see last diagram in Figure 9) and this would have led to an overestimate of that class’s area. It was resolved by clipping back the derived layer to the maximum extent of the Strategi® urbanised areas.

E. The clipped suburban area overlying the Chalk aquifer.

As the bedrock and superficial aquifer thematic layers are not mutually exclusive, a final stage (not required for the Luton and Dunstable example because superficial aquifer is not present) , in order to avoid double-accounting, was to assign the Suburban and Other Urban classes according to whether they overlay bedrock outcrop or subcrop.

Figure 9 Deriving suburban area using Luton and Dunstable as an illustration; diagrams A-C (BGS © NERC. This map is reproduced from Ordnance Survey topographic material with the permission of Ordnance Survey on behalf of The Controller of Her Majesty's Stationery Office, © Crown Copyright. Licence number 100017897/2007)

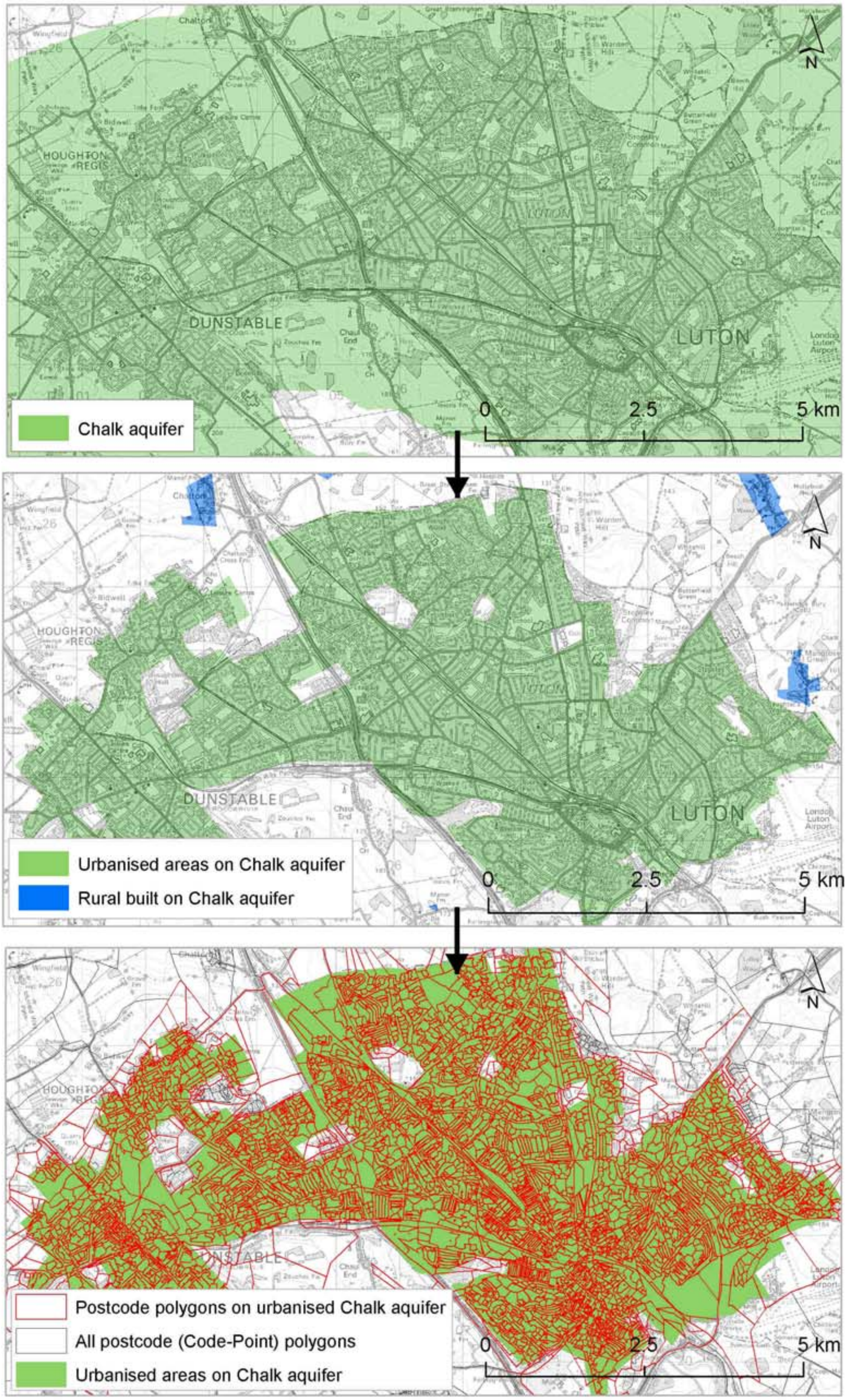
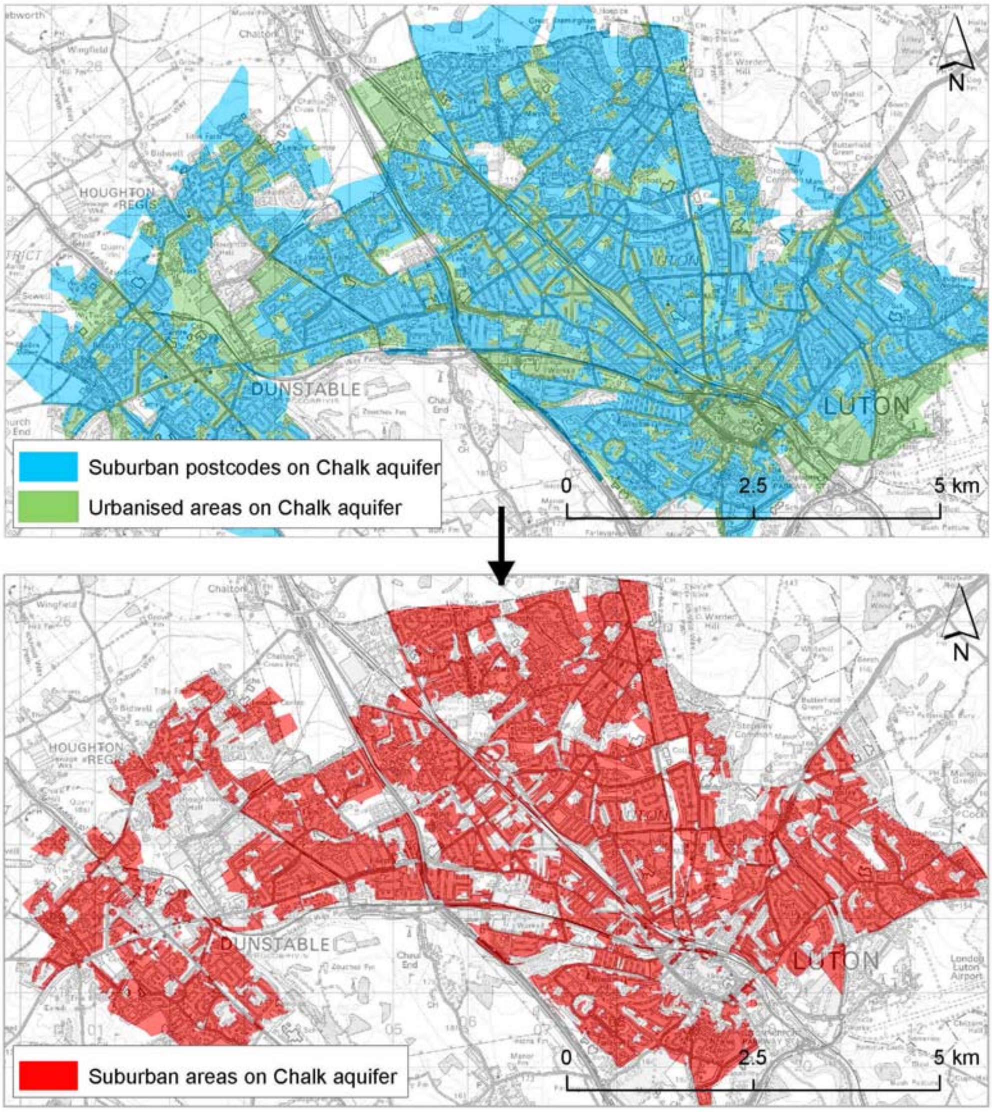


Figure 10 Suburban areas of Luton & Dunstable derived by GIS spatial analysis: diagrams D-E (BGS © NERC. This map is reproduced from Ordnance Survey topographic material with the permission of Ordnance Survey on behalf of The Controller of Her Majesty's Stationery Office, © Crown Copyright. Licence number 100017897/2007)



COMMENTS ON PROCEDURE AND DATASET CONSTRAINTS

While the procedure described above is a valid approach, it is an approximation and is subject to some uncertainty for the following reasons:

An aquifer or not an aquifer?

The national Hydrogeological Map of England and Wales, 1977 (10) provided the outcrop pattern and hydrogeological classification of aquifers on which the categorisation for this paper is based. The 1:625,000 scale of that map reflects both the linework scale of the underlying solid and Quaternary geology maps it employed (16, 17) and the synoptic intention of the map, which is used most typically for regional planning purposes. Although convenient, synoptic geological datasets have to drastically simplify both vertically and laterally complex sequences of rocks (into a small number of units) and also complex outcrop patterns. Users need to be aware of the simplifying assumptions inherent in their use. One particular consequence for this study was the selection of which stratigraphic rock groupings would be classed as productive enough to figure in the aquifers list in Table 5.

For example, while the Lower Cretaceous Sands were selected because these strata contain several regionally or locally productive aquifers, these are separated by intervening poorly permeable silty and clayey strata that form part of the larger stratigraphic group.

Similarly, the Coal Measures were included even though they comprise very significant thicknesses of (poorly permeable) mudstones. This was partly because of the permeability of intercalated fractured sandstone horizons and partly because very extensive former mining activities have, through collapse and subsidence, significantly expanded flow systems. A similar case could be made for the Mercia Mudstone Group but in the event it was excluded; although it contains some locally important sandstone horizons, this widely distributed formation is a predominantly mudstone sequence with evaporites in places and this limits its usefulness for groundwater supply.

A further complication arises from lateral variation in rock type of a particular formation arising from facies changes. For example sands in the Lambeth Group (Palaeogene Sands), the Upper Greensand (Lower Cretaceous Sands), and some productive Jurassic sandstones and limestones become progressively more clayey and less productive along their strike, developing into aquitards or even aquicludes.

Such features cannot be adequately represented at small scale, and a degree of subjectivity was unavoidable in those formations selected as significant aquifers. This could in part be addressed in future refinement exercises by basing the aquifer classification on a more detailed geological dataset, such as the BGS national coverage of solid and Quaternary geology at 1:50,000 scale (DigMap®). However, while the hydrogeological characterisation of this dataset is under way, the GIS computational requirements would need to be considered; the dataset comprises over 230,000 polygons and more than 500 formation names compared with the 1014 polygons and less than 60 formation names of the 1:625,000 map.

Urbanised or not urbanised?

Several different area values were trialled to provide an acceptable filter to separate rural built from urbanised land uses and these were tested in various locations. The 1 km² criterion was found to be effective and is considered to be the minimum area that will adequately separate this sub-class; a smaller area subsumed many villages, a larger area tended to exclude newer development on the outskirts of expanding towns. The criterion may cause an underestimate of ribbon development along some periurban arterial roads on town margins but on inspection these areas did not appear to be significant.

Suburban or not suburban?

In the same way, several different query formats were devised and compared in order to use the postcode dataset as an indirect method of identifying suburban areas (as opposed to industrial, commercial and dense urban residential land uses). Screening queries that used rules based on postcode areas were poorly correlated and discarded. Robust additional rules that could reliably relate address densities for a given postcode area might, in a future study, be an improvement. These could help define more precisely the suburban category of an urbanised area, especially where it is adjacent to denser urban residential land uses such as older terraced or newer multi-storey housing types.

The query criteria finally selected and described in the preceding section were devised empirically on a trial and error basis and tested on a range of sample districts in Oxfordshire, Berkshire and South Yorkshire. These were found to function satisfactorily in a range of urbanisation situations, from expanding market towns to older cities undergoing regeneration. However, a postcode analysis is not a direct measure of suburban land use, such as would be obtained, for example, by photogrammetric survey and it is possible that the extent of dense urban residential districts in some towns has been underestimated in favour of a suburban classification.

RESULTS

Area statistics for the 13 main bedrock and superficial aquifer groups are given in Table 6. These show the following features

- About 12% of the c.85,000 km² of bedrock and superficial aquifer in England and Wales is overlain by built land.

- Around 72% of this built land is urbanised (7,495 km²), with the balance rural/semi-rural (villages or ribbon development).
- None of the aquifer groups has more than about 20% of its outcrop/subcrop urbanised (although several, such as the Chalk and Permo-Triassic sandstones have significant cover of rural built).
- Of the 7,495 km² of urbanised land on bedrock or superficial aquifer, about 65% (4863 km²) is categorised as suburban, the balance being more dense urban residential, commercial, industrial or mixed land uses. This percentage may be a slight overestimate and may subsume some inner urban residential districts that would not normally be regarded as suburban.
- For each aquifer group, suburban land was about 60-70% of the urbanised cover and occupied typically less than 10% as a percentage of each group's outcrop/subcrop area (range 0.7-13.3%).

DISCUSSION

This first-pass analysis of the extent of urbanisation across the most widely used aquifers in England and Wales suggests that, at a total of around 9% of the outcrop/subcrop area, currently only a relatively modest proportion has been urbanised. Of the most productive aquifers, only the Permo-Triassic Sandstones and Magnesian Limestone exceed 10% by area. This is not particularly surprising as the UK follows a globally-recognised trend of settlement preferring to expand across coastal and lowland areas first, and as a number of important bedrock aquifer outcrops are upland areas, these have tended to remain predominantly rural. Being often scenically attractive too, many of these recharge areas have enjoyed at least partial protection through longstanding development controls conferred by land use planning instruments (e.g. National Park, Area of Outstanding Natural Beauty or greenbelt status) that have diverted urbanisation pressures. Thus it is those aquifers with extensive lowland recharge areas such as the Permo-Triassic Sandstones and the Coal Measures of the Midlands/northern England and the Palaeogene sands in the South East that have the highest percentage coverage and the predominantly upland Chalk (with the largest outcrop area of any aquifer) that has currently less than 6% urbanised land cover.

Suburban land is by far the most important urban land use category, estimated to typically occupy around two-thirds of all urbanised land and currently overlying about 4860 km² of aquifer outcrop. This is of comparable order to the DEFRA-commissioned projections of landtake on greenfield for 2001-2016 referred to earlier of 785-1479 km², although not all new dwelling construction on rural land would take place on aquifer or be exclusively suburban in nature.

An extrapolation of even the baseline housing completions rate of 150,000 per annum to 2051 (a rate which is widely viewed as falling well short of demand in southern and eastern and central England) would mean almost 7.5 million new dwellings constructed in England alone. If the ambitious governmental target of 60% new housing on pre-developed ('brownfield') land (18) cannot be achieved and maintained, the rate of landtake from presently rural land uses is certain to accelerate.

This could quite feasibly mean an expansion of suburban land use in England of one third or more of the present total, perhaps half of which would be at the expense of adjacent rural catchment.

Table 6 Extent of urbanisation and suburban/other urban categories on locally and nationally important aquifers in England and Wales

	Aquifer/Aquifer Group	**Outcrop area all landuses km²**	**Aquifer under All Built km²**	**Aquifer under Urbanised km²**	**Urbanised as % of all outcrop/ subcrop**	**Aquifer under Rural Built km²**	**Urbanised (Other Urban) km²**	**Urbanised (Suburban) km²**	**Suburban area as % of all outcrop/ subcrop**	**Suburban area as % of all urbanised**
Bedrock aquifer at surface or below superficial aquifer	Crag	3188	296	121	3.8	175	39.3	81.7	2.6	67.5
	Palaeogene Sands	3901	879	741	19.0	138	221	520	13.3	70.2
	Chalk	**19658**	**1870**	**1118**	**5.7**	**752**	**363**	**755**	**3.8**	67.5
	Lower Cretaceous Sands	**5368**	**559**	**315**	**5.9**	**244**	**100**	**214**	**4.0**	67.9
	Upper Jurassic Limestones & Sandstones	1651	139	73	4.4	66	24.8	48.2	2.9	66.0
	Middle Jurassic Limestones	**6559**	**453**	**229**	**3.5**	**224**	**89.3**	**140**	**2.1**	61.1
	Lower Jurassic Sands	211	25	14	6.6	11	5.65	8.35	4.0	59.6
	Permo-Triassic Sandstones	**10290**	**1636**	**1273**	**12.4**	**363**	**467**	**806**	**7.8**	63.3
	Magnesian Limestone	**1,404**	**222**	**175**	**12.5**	**47**	**52.7**	**122**	**8.7**	69.7
	Coal Measures	9915	2286	2006	20.2	280	735	1271	12.8	63.4
	Millstone Grit	8,893	572	387	4.4	185	141	245	2.8	63.3
	Carboniferous Limestone	8708	307	94	1.1	213	32.1	61.9	0.7	65.9
Superficial aquifer over bedrock non-aquifer	Quaternary Sands & Gravels, Blown Sand	5238	1149	949	18.1	200	360	589	11.2	62.1
Totals		**84,984**	**10,393**	**7,495**	**-**	**2,898**	**2,631**	**4,863**	**-**	**-**

Bold Extensive and highly productive aquifers

Predicting the impact of suburbanisation on adjacent presently rural areas used as the gathering grounds for groundwater public supply purposes will be a challenge. While there is a growing body of evidence that the quantitative effect of urbanisation is generally to increase recharge compared with the equivalent rural (agricultural or woodland) land cover (19, 20, 21), understanding of which parts of the urban land cover do this best is still at the qualitative stage. The likely general impact on water quality remains even more incomplete and fragmentary. There are results from a recent EU-supported comparative study of four case study cities in Germany, UK, Slovenia and South Australia that are dependent on local groundwater and where suburban land use is important (the AISUWRS project, 21). These suggest that suburban aquifers may not be under such severe contamination pressure from the constant emissions of the urban drainage system as may at first appear, providing appropriate protection measures are in place. However research in this area remains in its infancy.

The trend towards suburbanisation points to a growing need to hydrogeologically assess such catchments in terms of their role as an increasingly widespread land use type. Important national water management questions include:

- What will be the quantitative effect on recharge for presently rural groundwater catchments as they suburbanise- are we confident that the general tendency for urban recharge to be higher than the corresponding rural area applies to new suburbs? Will these catchments therefore still be able to support current groundwater public supply abstraction rates or will these supplies need to be substituted? If so, from where?
- Will future housing development need to consider the groundwater dimension more seriously in urban runoff drainage schemes where the development overlies an aquifer? For instance, by prioritising design that promotes infiltration of benign recharge (from roof and paved runoff or urban greenspace? If so, will this be implemented generally through building regulations, specifically through planning agreements or some other way?
- Will proposals for an accelerated rate of homebuilding, such as those espoused in the Barker Review (22), need to (or be able to) take account of groundwater recharge requirements as urbanised areas increasingly extend out over their groundwater supply catchments? If so, how will new housing targets be met; on the supply side (e.g. by further increasing unit density per hectare), or on the demand side (e.g. through migration controls to curtail population increase)?
- What will be the principal effects on the quality of recharge infiltrating beneath suburban catchments? Will groundwater supply treatment works need to take increasing account of the age and extent of catchment housing types (with their associated water supply, pluvial and foul drainage infrastructure) when planning future treatment requirements?

CONCLUSIONS AND RECOMMENDATIONS

GIS techniques employed to estimate the extent of urbanisation and suburbanisation land overlying locally and nationally important aquifers in England and Wales show that:

1. About 10,400 km² of the aquifer outcrop/subcrop lies beneath built areas, about 72% of which consists of urbanised land.
2. Approximately 65% of such urbanised land would be categorised as suburban, occupying an area of c.4860 km².
3. Urbanised land currently overlies only quite limited parts of aquifer outcrop/subcrop (about 9% in total), despite strong urbanisation pressures in southern, eastern and central England, where a number of extensive and highly productive aquifer systems are located.

Suburban land cover is likely to increase significantly in response to rises in the long-term rate of housebuilding, to meet projected shortfalls resulting both from increasing population and diminishing household size. An as-yet unknown proportion, possibly half, of the land required for suburban expansion will need to be allocated in previously undeveloped rural areas, generally on the periurban margins of existing urbanisation. As many of these same periurban rural areas also serve as catchments for both public supply pumping stations and private abstractions, there will be an impact on both the quantity and quality of recharge that supports these withdrawals, especially in southern Britain where urbanisation pressures are most intense but most of the more productive aquifers are located.

Recommendations include :

1. Better understanding of the impact of suburbanisation on recharge. This could be achieved by more applied research at catchment scale, with field verification, to quantify urban water cycle components, building on the innovative start made by urban groundwater studies like the EU-supported AISUWRS project. Such studies are difficult - the field is cross-disciplinary because the urban water cycle is complex and difficult to quantify - but are essential if the impact on recharge quantities and recharge quality is to be characterised sufficiently for predictive planning purposes.
2. Refinement of these first-pass estimates to provide greater precision and better definition of the aquifer outcrop on which urbanisation is occurring. This could be achieved through use of a more detailed geological dataset (such as that at 1:50,000). Improved demarcation of suburban and (more densely populated) urban residential districts might also be achieved by a refinement in the postcode query criteria.
3. Identification of the areas of aquifer most likely to urbanise before 2050 and of those groundwater public supplies most vulnerable to the consequent land use changes.

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REFERENCES

1. Eurostat (2007). Total population, Population projections, Population density and Average number of persons per private household on http://epp.eurostat.ec.europa.eu/portal. Accessed February 2007
2. Government Actuary's Department (2007). Population projections for United Kingdom and England and Wales, 2004-based Principal projection. http://www.gad.gov.uk/Population/index.asp?v=Principal&y=2004&subYear=Continue. Accessed February 2007
3. Office for National Statistics (2007). People and migration. http://www.statistics.gov.uk. Accessed February 2007
4. Office for National Statistics (2006) Population Trends #126, Winter 2006. ONS London
5. Holmans A (2006). More households to be housed: where is the increase in households coming from: technical document. Cambridge Centre for Housing and Planning Research
6. Communities and Local Government (2006) New Projections of households for England and the Regions to 2026. ODPM Statistical Release 2006/0042. *http://www.communities/gov.uk*. Accessed February 2007
7. Nixon J W (1970) Comment on 'Size and structure of the household in England over three centuries' by p Laslett. Population Studies 24 (3) 445-447
8. Department for Environment Food and Rural Affairs (2004) Study into the environmental impacts of increasing the supply of housing in the UK. Appendix F. http://statistics.defra.gov.uk/esg/reports/housing/default.asp. Accessed February 2007
9. ffice of the Deputy Prime Minister (2003) Sustainable Communities: Building for the Future London ..pp
10. Department of the Environment, Transport and the Regions (1997) Digest of environmental statistics. HMSO, London

11. Institute of Geological Sciences (1977) Hydrogeological map of England and Wales. IGS, London
12. Garcia-Bajo M and Lawley R (2004) Generation of superficial deposits-thickness maps and rockhead elevation contours for England, Scotland and Wales. GeoHazarD project. BGS Internal Report IR/04/082R. BGS Keyworth UK
13. Allen, D.J., Brewerton, L.J., Coleby, L.M., Gibbs, B.R., Lewis, M.A., Macdonald, A.M., Wagstaff, S.J. And Williams, A.T.(1997) The Physical Properties Of Major Aquifers In England And Wales. British Geological Survey Technical Report (WD/97/34). Environment Agency R&D Publication 8 Keyworth UK.
14. Jones H.K., Morris B.L., Cheney C.S., Brewerton L.J., Merrin P.D., Lewis M.A., Macdonald A.M., Coleby L.M., Talbot J.C., Mckenzie A.A., Bird M.J., Cunningham J., Allen D.J. And Robinson V.K.(2000). The Physical Properties Of Minor Aquifers In England And Wales. British Geological Survey Technical Report (WD/00/4). Environment Agency R&D Publication 68. Keyworth UK.
15. Ordnance Survey (2002) Code-Point User Guide v.2.0-5/2002
16. Institute of Geological Sciences (1979) Geological map of the United Kingdom 3rd edition, solid. Ordnance Survey, Southampton for IGS
17. Institute of Geological Sciences (1977) Quaternary map of the United Kingdom 1st edition. Ordnance Survey, Southampton for IGS
18. Communities and Local Government (2006) Planning policy statement 3 (PPS3): Housing. Communities and Local Government, London.
19. Foster S S D, Morris B L and Lawrence A R (1993). Effects of urbanisation on groundwater recharge. ICE International Conference on Groundwater Problems in Urban Areas, London, June 1993.
20. Morris BL, Lawrence ARL, Chilton PJ, Adams B, Calow RC, Klinck BA (2003). Groundwater and its Susceptibility to Degradation: A Global Assessment of the Problem and Options for Management. Early Warning and Assessment Report Series RS.03–3. United Nations Environment Programme, Nairobi, Kenya
21. Wolf L, Morris B and Burn S (2006) AISUWRS: Urban Water Resources Toolbox: integrating groundwater into urban water management. IWA Publishing London 296pp
22. Barker K (2006) Barker Review of land use planning. Final Report-recommendations. HM Treasury publication, HMSO Norwich

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