

Identifying crop vulnerability to groundwater abstraction: modelling and expert knowledge in a GIS

Chris Procter^{1*}, Lex Comber¹, Mark Betson¹, Dennis Buckley¹, Andy Frost¹, Hester Lyons¹, Alison Riding¹, Kevin Voyce²

¹Environment Systems,
ADAS,
Wergs Road, Wolverhampton,
WV6 8TQ, UK

² Environment Agency,
Hafren House, Welshpool Road
Shelton, Shrewsbury,
SY3 8BB, UK

* Contact author
Email chris.procter@adas.co.uk

Abstract

Water use is expected to increase and climate change scenarios indicate the need for more frequent water abstraction. Abstracting groundwater may have a detrimental effect on soil moisture availability for crop growth and yields. This work presents an elegant and robust method for identifying zones of crop vulnerability to abstraction. Archive groundwater level data sets were used to generate a composite groundwater surface that was subtracted from a digital terrain model. The result was the depth from surface to groundwater and identified areas underlain by shallow groundwater. Knowledge from an expert agronomist was used to define classes of risk defined in terms of their depth in metres below ground level. Combining information on the permeability of geological drift types further refined the assessment of the risk of crop growth vulnerability. The nature of the mapped output is one that is easy to communicate to the intended farming audience because of the general familiarity of mapped information. Such GIS-based products can play a significant role in the characterisation of catchments under the EU Water Framework Directive especially in the process of public liaison that is fundamental to the setting of priorities for management change. The creation of a baseline allows the impact of future increased water abstraction rates to be modelled and the vulnerability maps are a format that can be readily understood by the various stakeholders. This methodology can readily be extended to encompass additional data layers and for a range of groundwater vulnerability issues including water resources, ecological impacts, nitrate and phosphorus.

Keywords: abstraction, groundwater, vulnerability, GIS

1. Introduction

The Water Framework Directive (EC, 2000) has radically altered the management of the water environment within the EU. It rationalises water legislation, including five previous Directives, and embodies the concept of integrated river basin management. It sets out environmental objectives for water status based on:

- Ecological and chemical parameters.
- Common monitoring and assessment strategies.
- Arrangements for River Basin administration and planning.
- A Programme of Measures in order to meet the objectives.

The Water Framework Directive (WFD) approach promotes integrated management at the River Basin level. Because it is a Framework Directive, it provides common approaches and common objectives, principles, definitions and measures. However, the specific measures required have to be determined at the local level. This is the role of the ‘competent authority’, The Environment Agency in the UK. The WFD sets several stages in the protection of the River Basin District including

- “Setting environmental objectives” (Article 4), established in the context of environmental pressures on the quality and quantity of water resources;
- “Achieving water quality objectives” specifying that information must be collected on the type and magnitude of the *significant* anthropogenic pressures on surface water and groundwater bodies.

Once the (‘significant’) pressures have been identified, their impact must be assessed. This paper describes work that identifies areas at risk from groundwater abstraction

The Environment Agency (EA) is responsible for the management of water resources in England and Wales. One of their roles is to monitor and manage groundwater abstraction; Catchment Abstraction Management Strategies (CAMS) were developed by the EA to do this (Environment Agency, 2002). The objectives of CAMS include informing the public on water resources and licensing practice, recognising the needs of water users and the environment and to facilitate increased public involvement in catchment water resources management. CAMS are developed through a process of consultation with local stakeholders.

The Environment Agency (EA) has responsibility for the operation and development of the Shropshire Groundwater Scheme (SGS), which periodically abstracts water from Shropshire aquifers in order to supplement the river Severn. Over the past 20 years of development SGS has grown to become one of the largest groundwater augmentation schemes operating in the UK. Developed solely within North Shropshire, the scheme abstracts water from Permo-Triassic sandstone formations via a number of clustered pumping stations. From the outset, abstraction of groundwater on a scale permitted by the scheme has been a cause of concern amongst the local agricultural community. The principal concern was the perceived detrimental effect of groundwater abstraction on soil moisture availability for plant growth, and therefore impacts on crop yield/profit for individual farm businesses. The objective of this work was to identify and present in a clear and robust format for stakeholders, areas where soil water availability to crops would be potentially vulnerable to the lowering of the water table due to water abstraction.

Whilst other work modelling abstraction has considered many other aspects of the impact of groundwater abstraction, as yet there has been no systematic evaluation of the potential impact on agricultural production. Other studies have considered the impacts on water quality within a GIS (Al-Adamat *et al.*, 2003), the risk of pollution to groundwater (Lytton *et al.*, 2003), the effect on natural vegetation of abstraction (Munoz-Reinoso, 2001), the impact of abstraction on wetland status (Acreman *et al.*, 2000) and on fish stocks (Strevens, 1999). In this work we report on the assessment of crop vulnerability to water abstraction from the North Shropshire Permo-Triassic sandstone formations to augment the flow of the River Severn by the Environment Agency.

2. Background

The importance of groundwater is easily overlooked, as it is an out of sight, and all too often out of mind, hidden asset. In the UK groundwater supplies approximately 30% of the public water supply in England & Wales, 7% in Northern Ireland, and 3% in Scotland (Downing, 1998). By 2020 water use is expected to increase by 40% (World Water Council, 2000). Climate change models would indicate the need for more frequent water abstraction in schemes, as lower summer rainfall is predicted for parts of the UK (Hulme *et al.*, 2002).

Whilst the EU Water Framework Directive makes it incumbent upon member states to implement controls on abstractions to control impacts on the ecological status of rivers and lakes, the situation is not so clear for abstractions to supplement river levels that may impact terrestrial ecology or commercial agriculture. Crop yield and especially finish quality are strongly linked to water supply at key growth stages, as demonstrated by the extent of irrigation practices in the drier parts of Eastern England (Weatherhead *et al.*, 1997). In areas that have historically had an adequate soil water supply, without recourse to irrigation, there is a risk that as water abstraction rates increase and water levels fall, agricultural yields may decrease and organisations with responsibility for water abstraction may find themselves facing claims for compensation.

Other work considering abstraction in relation to soil moisture work has sought to assess the scale of irrigation practices and to spatially quantify the volume of water abstractions (Dunn *et al.*, 2003), or developed maps of soil moisture based on purely biophysical, climatic data (Svetlitchnyi *et al.*, 2003). However soil water and aquifers depends inherently on the underlying geology and for arable crops, the depth of the rooting profile. As yet research relating the impacts of water abstraction to specific land practices has not been forthcoming. In this work we describe a method for determining and visualising the spatial locations of areas vulnerable to ground water abstraction. The approach combines different data and analysis methods inside a Geographic Information System (GIS):

- Point source data (borehole records) of the depth to water table;
- Interpolation (kriging) to create piezometric surface;
- Classes of rooting zones associated with different levels of crop vulnerability from expert knowledge;
- Digital elevation model (DEM) data;
- Geological mapping to identify areas of major, minor and non-aquifer;

- Application of drift domain mapping to characterise intervening drift by its likely permeability.

The kriging approach has been used previously with groundwater vulnerability mapping of nitrate risk (Lovett *et al.*, 2001a; 2001b) in England and Wales where disjunctive kriging techniques (Oliver 1991; Rivoirard 1994) were used with predicted borehole nitrate levels for 2017. The resulting interpolated lattice points were matched to pre-defined vulnerability classifications through point-in-polygon techniques to spatially map risk.

3. Methods

3.1 Overall

The overall approach is conceptually elegant: archive groundwater level data sets are used to generate one composite groundwater surface; this surface is subtracted from a digital terrain model (DTM); the resulting figure is the distance from surface to groundwater. Having identified areas underlain by shallow groundwater the designation of risk vulnerability of crop growth being affected by abstraction is further refined by characterising the permeability of the intervening drift type(s). The stages in the approach to identifying different zones of vulnerability are:

1. Generate a water table surface
2. Determine depth to groundwater
3. Impose expert constraints
4. Refine designation of vulnerability by applying drift domains

3.2 Data and study area

The study area was approximately 15km by 15km and is shown, with the 5 abstraction points, in Figure 1. The borehole data were provided by the EA in Hydrolog format, for 128 borehole sites inside the study area and 5 outside. A 5m digital terrain model from Intermap Technologies recorded surface height with a stated vertical accuracy of $\pm 1\text{m}$. British Geological Survey Geology mapping was used to generate a mask of minor or non-aquifers within the study area. It is noteworthy that some operational and test abstraction has taken place at a number of sites in the study area.

[insert figure 1 about here]

3.3 Kriging

The borehole records provided by the EA spanned the period 1971-2003 and included information on the location of the borehole (eastings and northings), the date of measurement, and the depth to water table expressed as metres above ordnance datum. From these records, data were extracted from all of the 133 sites that fulfilled the following criteria: not within 2 years of operational pumping; not within 1 year of test pumping; within a growing season of April to September; and, had more than 20 readings / records. The rationale for the of selection these criteria was to create a Soil Moisture Vulnerability map that represented the worst-case scenario, that is one where the water table is represented as close to the surface as it is ever likely to be. It should be noted that the filters excluded borehole data from the study that might have been affected by abstraction from the 5 abstraction sites, thereby avoiding the any

spatial autocorrelation. This way, all areas that could potentially be at risk from the impacts of abstraction would be identified.

Having been filtered, for each borehole, the 95th percentile was extracted to minimise the impact of extreme (low drought or high recharge events) records in the generation of a trend surface from these point data. The rationale for filtering the data in this way was the study objective to model the groundwater levels under normal conditions, during the growing season.

The borehole depth to groundwater data for all 133 boreholes (after filtering their data) was kriged. A key statistic within geostatistics is the semivariance $\gamma(h)$, defined as half the mean squared difference between pairs of sample data values separated by a given distance or lag. It is estimated using the following formula (Trangmar *et al.*, 1985):

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [Z(x_i) - Z(x_i + h)]^2$$

where

$N(h)$ is the number of sample pairs at each distance interval h

$Z(x_i)$ and $Z(x_i + h)$ are the values of the variable at any two sampling locations separated by distance h .

By plotting semivariance at different distance lags (different distances apart over space), a semivariogram can be produced. The semivariogram has two main applications; that of structure recognition (the nature and scale of the spatial variation present) and that of optimum interpolation through kriging. Semivariograms have many different forms *e.g.* linear, spherical, exponential (Haining, 1990) and inferences can be drawn from the shape of the semivariogram about both the magnitude (the extent to which spatial variations in a value are predictable over space) and scale (the distances over which spatial similarity is observed) of spatial dependence in distributions. Data with no spatial structure (*i.e.* randomly distributed) will have a semivariogram that is flat.

In geostatistics, the semivariogram is used as the interpolative tool. The method of kriging estimates values for unsampled locations on the basis of weighted neighbouring values predicted from the semivariogram. Kriging is an exact interpolator because it preserves the sampled data values whereas other spatial interpolators, for example inverse distance weighting, can alter the values of data at sampled locations. The advantage of the use of kriging is that a map can also be produced of the associated standard errors associated with the interpolation.

3.4 Refinement

The approach incorporated 4 stages

1. the generation of a water table surface by kriging the borehole depth to groundwater data and comparison with local expert hydrological knowledge;
2. Determining the depth to groundwater by subtracting the kriged surface was subtracted from a DTM;
3. The imposition of agronomy constraints to identify different crop risks in terms of their depth in metres below ground level;

4. The application of drift domain mapping to further refine the results and the designation of vulnerability. The extent and permeability of any intervening soil and drift deposits as permeability will influence movement of water between the sandstone aquifer and the rooting zone.

The results are described the sequential application of these 4 stages to the data.

4. Results

Stage 1 Generate a water table surface

Semivariogram models were fitted by weighted least squares regression (Cressie, 1985) and comparisons between model types (spherical, exponential, gaussian) were made by observation of residual sum of squares. Where evidence of drift or trend was observed in the data, trend removal was carried out to investigate the presence of a trend masking nested spatial structure due to non-stationarity (Cressie, 1991).

On the basis of this preliminary investigation, the borehole point data were then kriged using the LOESS algorithm (Cleveland, 1979; Cleveland and Devlin, 1988) to a 25m grid creating a groundwater surface. The LOESS model is a modern interpolation algorithm, designed to fit simple models to subsets of the data, thereby constructing a function to describe the variation in the data. Semivariograms were computed at 250 meter and 500 metre lags. Each lag class was represented by at least 30 pairs of points, and the maximum lag was specified as half of the total distance measured in the field as directed by Journel and Huigbregts (1978).

A semivariogram of the raw data was produced with a lag of 250m for initial investigation. A relatively strong linear trend was identified in the dataset which required trend removal to investigate the presence of a trend masking spatial structure due to non-stationarity (Cressie, 1991). A local regression model was fitted to investigate the trend and the residuals produced from this model were then used to estimate the semivariogram with the trend removed.

Outliers were identified (later found to be located within the areas of drift or in perched areas) and investigated by importing the data into GEO-EAS a set of interactive software tools for performing two-dimensional geostatistical analyses of spatially distributed data (GEO-EAS, 2005). Each class was investigated systematically to identify pairs of points that had significantly high residuals. These points were then removed one by one re-plotting the variogram after each removal to visualise the effects

The next step was to fit the model to the variogram. This can initially be done using a visual estimation. Using the eye a spherical model would best suit the data, with a sill of approximately 10, range of 4000 and a nugget of 2. Using visual fitting the objective was reduced to 60. It is, however, possible to take these initial model estimates and iterate a more robust model using weighted non-linear least squares (Cressie, 1985). The results of iterating the model produced a much better fit with an objective of just 24.265 using the 250m lags. The values estimated were Range: 4607.105, Sill: 8.648162, Nugget: 1.980064. Using the 500m lags the objective can be lowered yet further (10.737), and the variables estimated for the 500m lags were Range: 4936.64, Sill: 8.724327 and Nugget: 2.065438. The fit of the 500m semivariogram was preferred with fewer outliers before maximum variance (gamma)

is reached. Figure 2 illustrates the difference between semi-variograms constructed using lags of 250m and 500m.

[insert figure 2 about here]

The Kriged residuals were added back into the LOESS model to give the groundwater surface (Figure 3.).

[insert figure 3 about here]

The interpolated ground water surface was visually compared with an expert hydrologist's manual placement of different trends in the surface (see Figure 4). Whilst this is only a visual comparison (the expert drew their contours at 5 and 10 metre intervals) the comparison is good except for the southwestern corner where the data were sparse (and outside the aquifer area).

[insert figure 4 about here]

Stage 2 Determine depth to groundwater

To produce a depth to groundwater map, the kriged surface was subtracted from the Intermap Technologies digital terrain model. This is shown in Figure 5 and highlights regions where the water table is close to the surface and therefore may be at risk from any drawdown of the water table by pumping. Note that areas of non-sandstone aquifer from the British Geological Survey solid geology data were masked from the study area due to the lack of hydrological connectivity with the sandstone and because the Shropshire scheme abstracts water from Permo-Triassic sandstone formations.

[insert figure 5 about here]

Stage 3 Impose expert constraints

A local agronomist with expert knowledge of agricultural practice in the study area defined classes of risk appropriate for its cropping. Four risk classes were defined in terms of their depth in metres below ground level (mbgl) as follows:

Class 1 Water table shallower than 1.5 mbgl

Possible impact on wetland habitats and agricultural crops abstracting soil moisture to a maximum depth of 1.5 mbgl, e.g. potatoes, onions, carrots, vegetable brassicas, peas, beans and established grassland on mineral soils.

Class 2 Water table between 1.5 and 2.5 mbgl

No impact on vegetation or crops in Class 1. Possible impact on deeper rooting agricultural crops abstracting soil moisture to a maximum depth of 2.5mbgl, e.g. cereals, oilseed rape, maize, sugar beet and perhaps grassland growing on peaty soils.

Class 3 Water table between 2.5 and 4.0 mbgl

No impact on vegetation or crops in Class 1 or 2. Possible impact on established trees.

Class 4 Water table deeper than 4.0 mbgl

Lowering of water table by groundwater abstraction from the sandstone aquifer will not impact significantly upon soil moisture availability to any vegetation.

Areas underlain with low permeability drift.

Land where low permeability layers within the drift sequence separate near-surface soil water from the Permo-Triassic sandstone aquifer. Lowering of water tables by groundwater abstraction is unlikely to affect crops or other vegetation growing in any of the classes above.

These constraints were imposed on the depth to groundwater map and resulted in a classified water abstraction risk map (Figure 6). Despite the water table being relatively close to the surface in this region, the area at risk of water table drawdown pumping is still relatively small.

[insert figure 6 about here]

Stage 4 Application of drift domain mapping

Soil moisture vulnerability cannot be assessed simply by calculating depth to water table alone as this would lead to an over estimation of the actual risk. The degree of risk was further refined by considering the extent and permeability of any intervening soil and drift deposits. The degree of permeability will have a significant influence on movement of the water table between the sandstone aquifer and the rooting zone, and therefore the designation of vulnerability. For the purpose of the assessment, drift types were grouped into domain categories based on their relative permeability. These groups were further sub divided to denote decreasing permeability within the group subset. Descriptions and illustrations of this are shown in Figure 7.

[insert figure 7 about here]

5. Discussion

The objective of this work was to identify vulnerable areas (associated with rooting zones) to potential water abstraction activities. The principal value of this mapping is as a tool for indicating to farmers whether their holdings lie in vulnerable zones and therefore whether any decrease in crop yields are potentially attributable to reduced soil moisture. The simple model presented here offers an elegant solution within a practical implementation related to an actual policy context. The nature of the mapped output is one that is easy to communicate to the intended farming audience because of the general familiarity of mapped information.

There are a number of other features of the method and output that are worth noting. First, we have adopted a low risk strategy that assumed the worst case. Records up to the 95th percentile of qualifying borehole records was used to ensure that the water table values were as close to the land surface as possible. Using the 95th percentile as a threshold ensures the data were not influenced by large outliers associated with low groundwater levels under drought years or high groundwater levels in years recording excessive recharge. Second the selection of risk categories took account of the error in the elevation model data. Typical values for rooting depth for arable crops are 0.8m to 1.0m. In this work the upper limit of the most 'at risk' category was set at 1.5m. Third, the output establishes a baseline against which future abstraction activities can be compared. Fourth, the kriged water table surface was very similar to an expert hydrogeologist's manual drawing of the location of the aquifer, based on his heuristic local knowledge.

This work shows that as water resources become scarcer, some of the fears about the impact of abstraction on other land-based activities such as agriculture can be allayed. The establishment of the depth to ground water were based on historical data collected over a 30 year period and provide a robust baseline against which to monitor the impacts of future possible abstractions for a range of wider societal interests.

This methodology can readily be extended to encompass extra data layers from potentially diverse sources. For example spatial data (e.g. soil characteristics) could be combined with site-specific data from, for example survey results, and expert judgement to derive a vulnerability classification. Alternatively the vulnerability classification may be based on the co-location of data layers that represent a particular mechanism of risk (e.g. Lake *et al.*, 2003). The approach is suitable for a range of groundwater vulnerability issues including water resources, ecological impacts, nitrate and phosphorus. For instance, by modelling ecological knowledge of wetlands a map of the vulnerability of water sensitive habitats could be produced.

6. Conclusions

The major advantages of the methodology presented here were that it integrated existing data using a simple, defensible, methodology to indicate areas at risk and not at risk. The outputs reflected local expert knowledge, were accessible to interested parties and brought together all the stakeholders interested in the mapping of soil moisture vulnerability (farmers, the Environment Agency, water experts).

At a stakeholder group meeting in April 2004 the vulnerability maps were presented. The group was comprised of senior technical advisors and local members of the National Farmer's Union, the Country Land and Business Association, Shropshire County Council, the Environment Agency and English Nature. The maps were very well received by the members of the committee who considered that the maps represented a significant innovative leap forward in understanding and quantifying the true level of vulnerability posed by the Scheme. The format of the maps brought together and presented 20 to 30 years worth of technical data in a format that could be readily understood by non specialists.

A dataset has been developed that is of immediate practical value to water regulators responding to enquiries from land owners with respect to the potential impact of abstraction or reduced recharge on the soil water supply for commercial crops. The final product and the method of derivation is easily understood and communicated to all stakeholders. The vulnerability maps and the risk assessment methodology have provided a number of additional outcomes:

- A vehicle with which to counter long established misconceptions about the risks posed by the Scheme;
- The creation of a baseline to allow the impact of future increased water abstraction rates to be modelled;
- The maps allow the Environment Agency to better target monitoring efforts and resources in order to assess potentially vulnerable areas as the growing burden of groundwater monitoring as the Scheme develops and expands.

Such Geographic Information-based products have a significant role to play in the characterisation of catchments under the WFD, and especially the public liaison that

is fundamental to the setting of priorities for management change. As the responsible body for the implementation of the WFD in the UK, the Environment Agency has a need to further explore the application of existing analytical tools to its data resource, to characterise and manage the pressures on environmental resources. It is appropriate that the tools adopted are not overly complicated and that the stakeholders, in this case the National Farmers Union, are involved in the development of the pressures and impacts methodology. It is also essential that uncertainty is taken account of in the risk assessment and properly documented. In this case, a risk averse strategy in the selection of mapped groundwater levels and crop rooting depths was taken to define a worst-case envelope.

The integration of datasets describing intrinsic and specific risk, and of environmental models, is playing a key part in the implementation of the WFD. The directive has resulted in a number of GI initiatives that are making full use of the functional capabilities of GIS. The further expansion of the portability of geographic information and of decision making described here extends that which was achieved in the SNIFFER Screening Tool (Lord *et al.* 2003).

The Shropshire groundwater model is the first time a GIS has been used to model water management (in this case groundwater abstraction) in response to WFD and CAMS objectives. Without the GIS, the knowledge held by local (EA) experts about the dangers to crops of water abstraction could not be rigorously and independently demonstrated to the stakeholders. The desktop versions giving access to visualisation of the data have allowed the implementation of the WFD to be progressed. This directive may prove to be a catalyst in the use and development of GIS applications as forest management was for the US and Canada in the early 1980's.

This is the first step in a potential series of increasingly complicated unions of geo-referenced data, spatial analyses and models within a GIS framework for the management of water quality and quantity.

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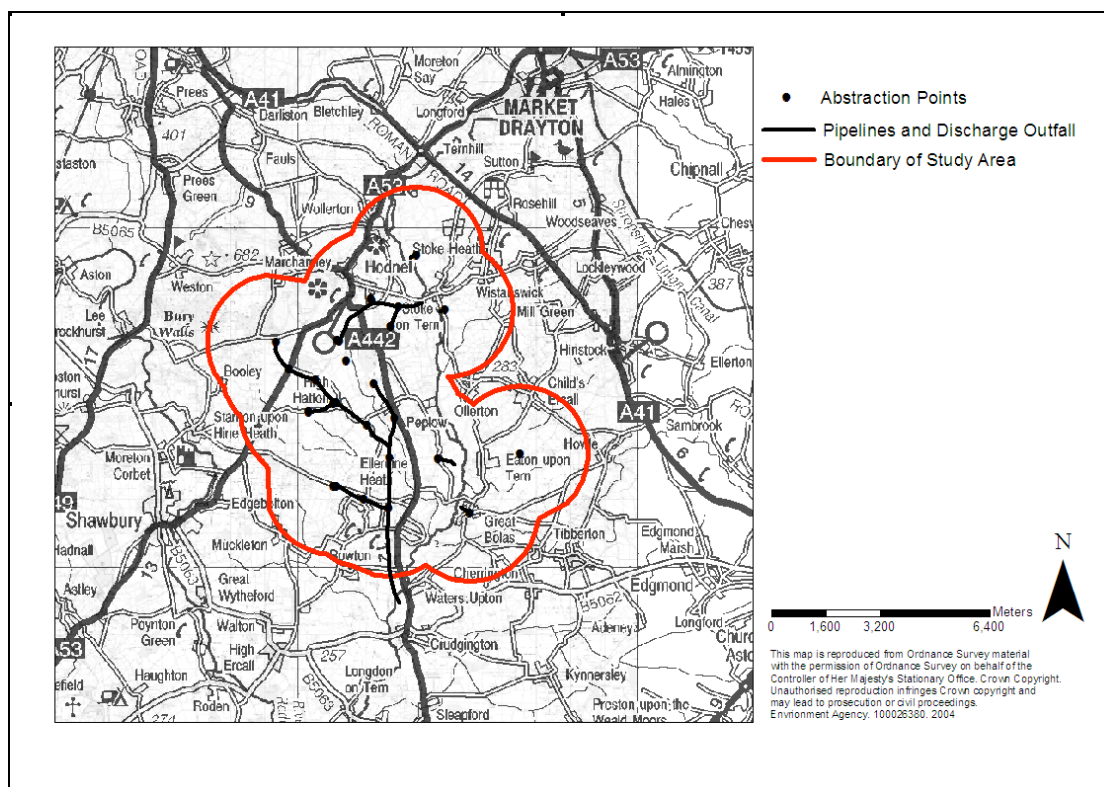


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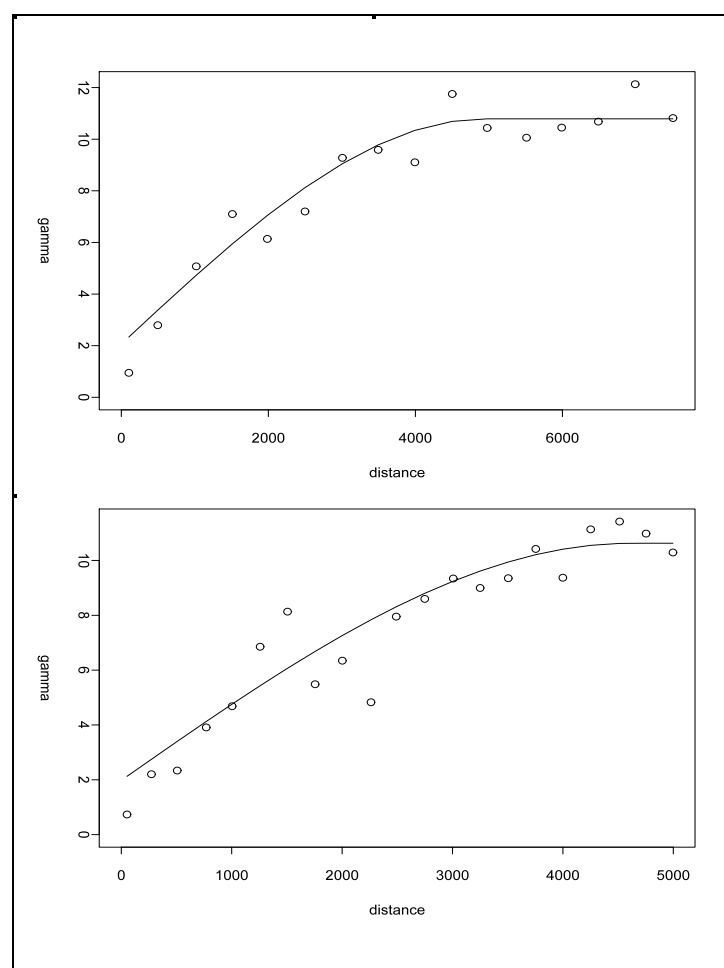


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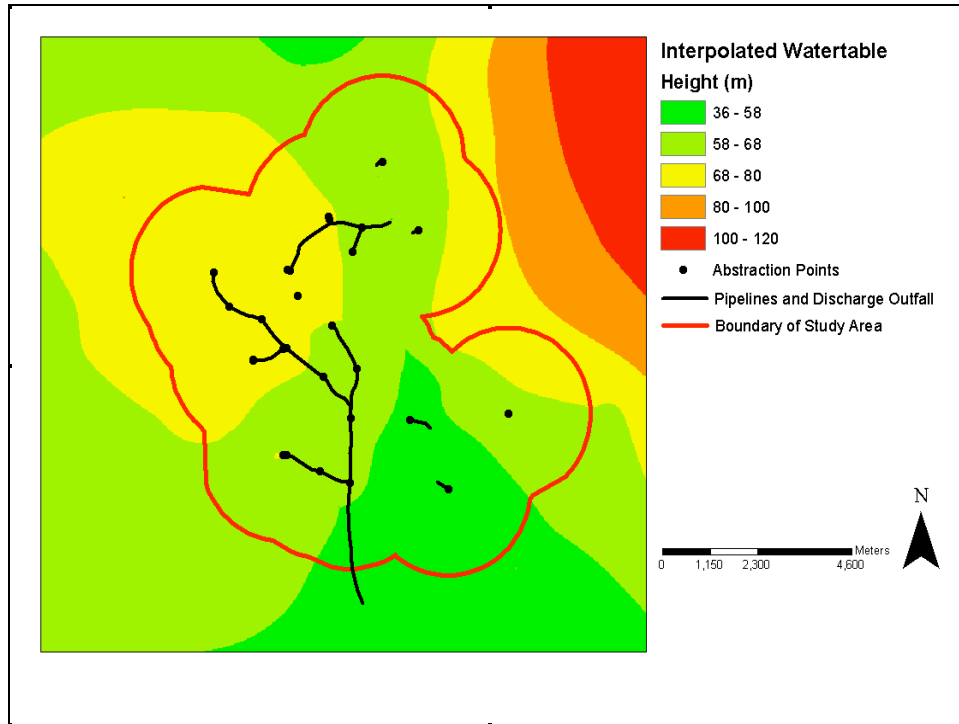


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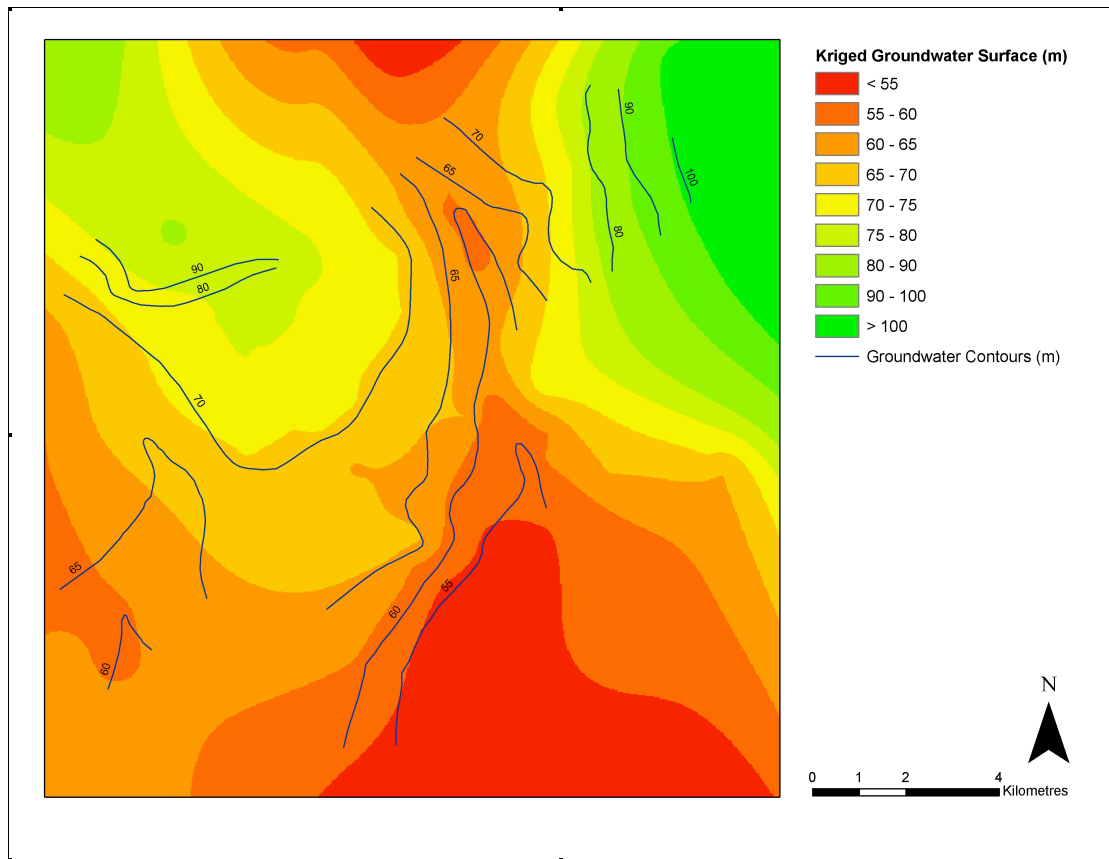


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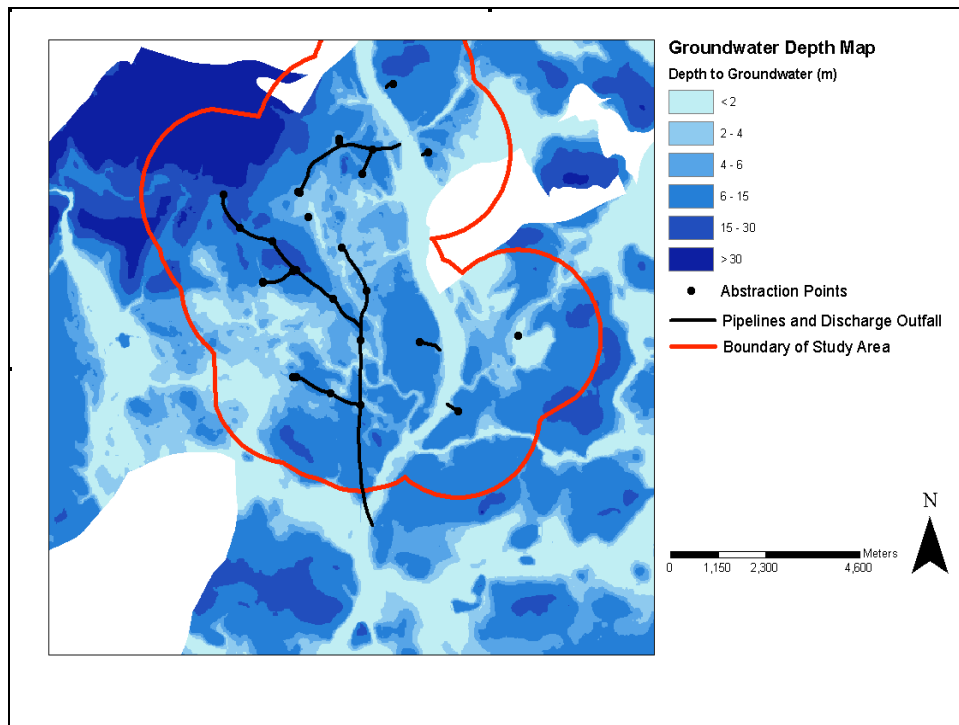


Figure 5. Depth to groundwater (metres below ground level)

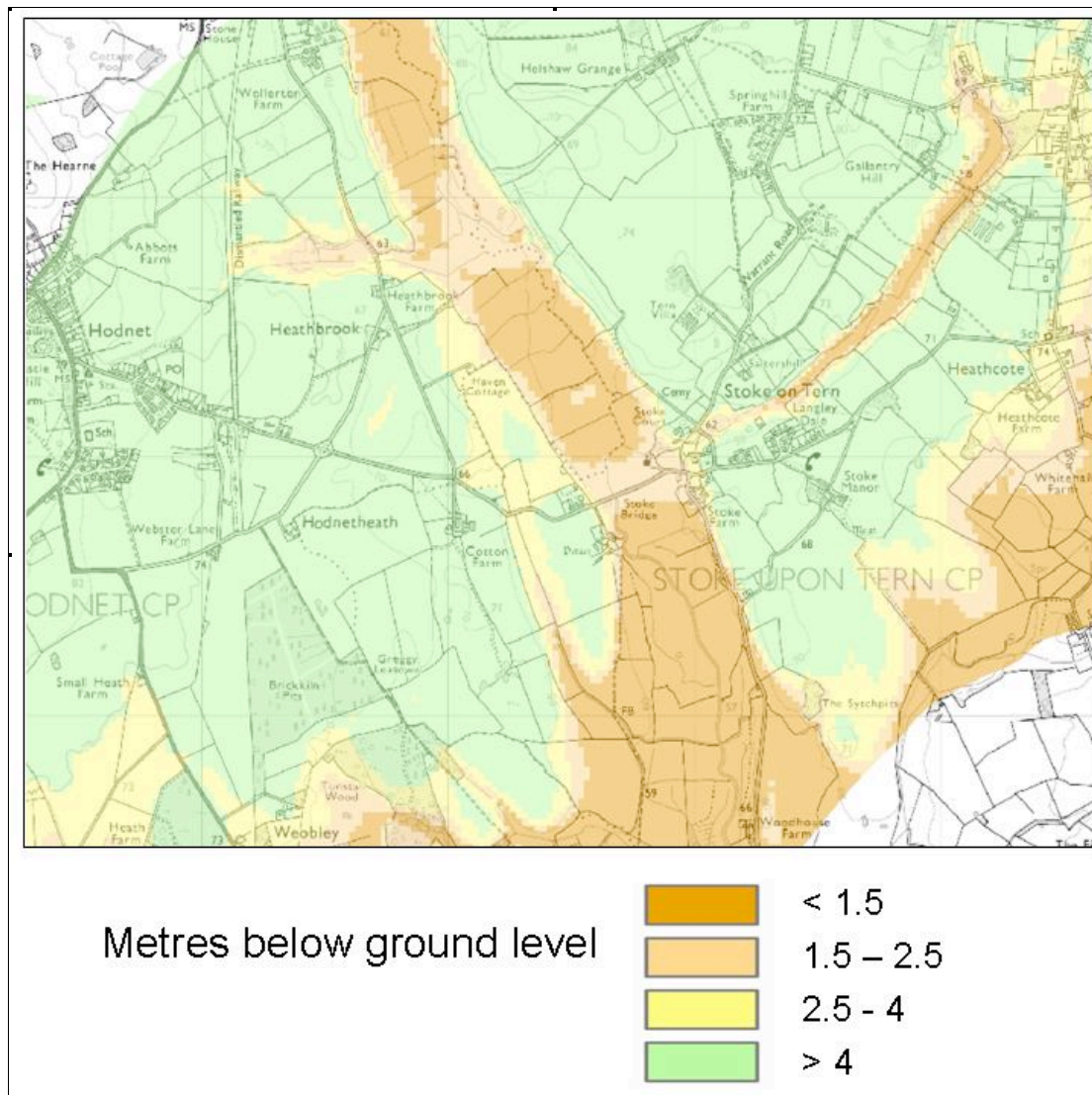


Figure 6. Depth to groundwater abstraction for the study area and in detail, with context from OS 1:25000 mapping.

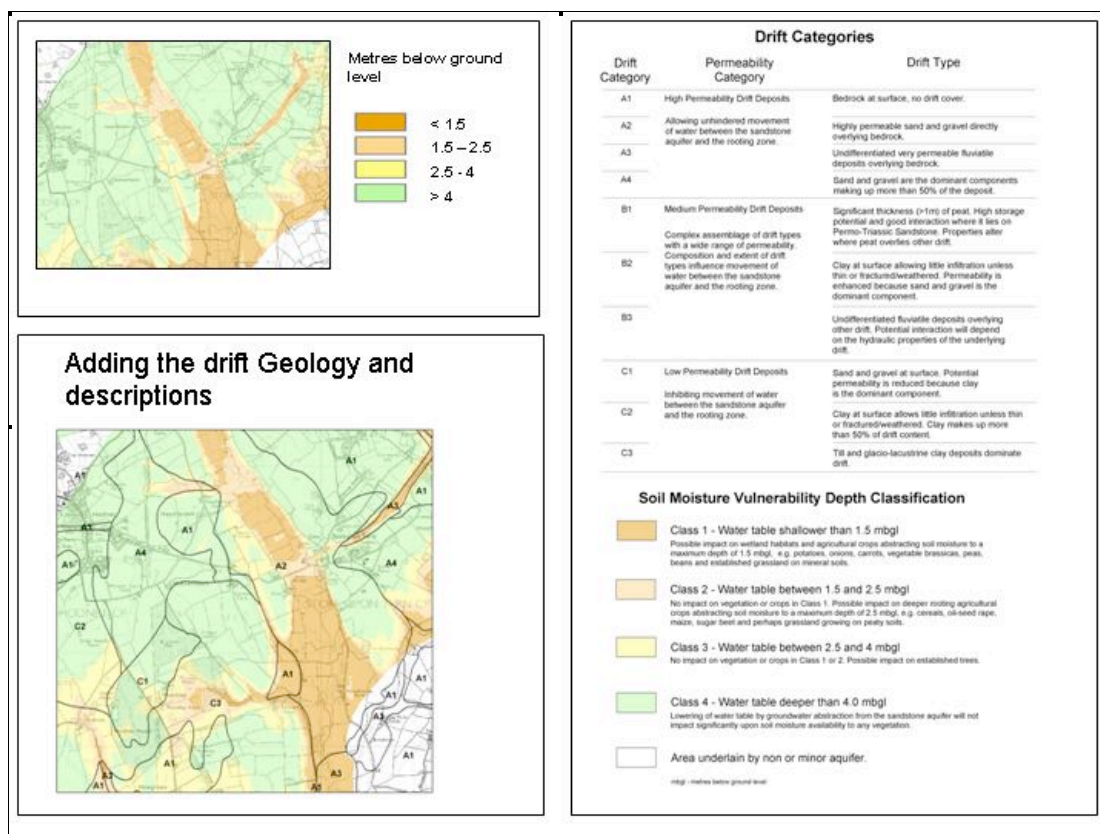


Figure 7. Refinement of areas vulnerable to abstraction using drift geology