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A DIAGNOSTIC METHOD TO DETERMINE AQUIFER SUSCEPTIBILITY

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3 Susceptibility to subsidence

Susceptibility to subsidence: $S = S1 + S2$
Qualifier relating to the rate of occurrence: $Sq = S3 + S4$

3.1 Aquitard Compressibility - S1

Notes: 1 Pa = 1 N/m^2 = 1 $kg/m/s^2$

Suggested Weighting **/Pa**	$>10^{-6}$ 3 10^{-6} - 10^{-8} 1 $<10^{-8}$ 0
Massimo Civita	
Robin Herbert	(Comment refers to rate of subsidence)
Harriet Nash	
Alain Dassargues	$> 10^{-6}$ 4 10^{-6} - 10^{-8} 2 10^{-8} - 10^{-10} 1 $<10^{-10}$ 0
Jaroslav Vrba	
Antonio Bosch	
Lucila Candela	
Nathalie Doerfliger	$>10^{-6}$ 3 10^{-6} - 10^{-8} 2 $<10^{-8}$ 1
Javier Temino Vela	$>10^{-6}$ 3 10^{-6} - 10^{-8} 1 $<10^{-8}$ 0
Doug Kelly	
Ann Williams	
Revised Weighting	$>10^{-6}$ 3 10^{-6} - 10^{-8} 1 $<10^{-8}$ 0

[2.4 Comments]

Massimo Civita	In ??? Karstic complexes or hydraulic conductivity over 100 m/d is normal. In Sardinia Pb-Zn mineral district, too
Robin Herbert	
Harriet Nash	
Alain Dassargues	I don't understand exactly what you mean when you mention "I4 is used as a qualifier"
Jaroslav Vrba	
Antonio Bosch	
Lucila Candela	
Nathalie Doerfliger	Is it the case of a confined aquifer? (Diagram) The overlying formation of low permeability of the aquifer!
Javier Temino Vela	
Doug Kelly	
Ann Williams	10 m/d is very permeable for an aquitard. Where is the aquitard supposed to be?
Revision	

2.4 Permeability of Aquitard - I4

Notes: This is a qualifier Iq, it moderates the rate of intrusion but does not affect the eventual scale.

Suggested Weighting **m/day**	>10 3 10^{-3} - 10 2 $<10^{-3}$ 1
Massimo Civita	>100 5 10 - 100 3 10^{-3} - 10 2 $<10^{-3}$ 1
Robin Herbert	Tick
Harriet Nash	
Alain Dassargues	
Jaroslav Vrba	
Antonio Bosch	
Lucila Candela	>1 3 10^{-3} - 1 2 $<10^{-3}$ 1
Nathalie Doerfliger	Tick
Javier Temino Vela	>1 3 10^{-3} - 1 2 $<10^{-3}$ 1
Doug Kelly	
Revised Weighting	>10 3 10^{-3} - 10 2 $<10^{-3}$ 1

[2.3 Comments]

Massimo Civita	OK
Robin Herbert	
Harriet Nash	Would layering be a useful index to barriers? - but probably only in limited situations (ignore comment).
Alain Dassargues	
Jaroslav Vrba	
Antonio Bosch	Also seems very good to me; given that the position of the freshwater/saline water contact depends - also - on the rate of flow to the sea, expressed in flow units, this could also be considered for inclusion; obviously it is included in an indirect way in the gradient, although you could express it in terms of recharge to the aquifer...
Lucila Candela	
Nathalie Doerfliger	Presumably natural barrier due to the presence of impermeable layer in the zone of the contact between sea/ocean and the underground of the island or the land = hydraulic barrier.
Javier Temino Vela	
Doug Kelly	
Ann Williams	Heterogeneity also affects saline intrusion - Oman experience shows that sea water can come in very fast along permeable layers, this can be considered a negative barrier.
Revision	Include facility fo recognition of highly permeable layer which would enhance potential for saline intrusion.

2.3 Barrier Effectiveness - I3

Notes: As the existence of barriers may not be obvious, this factor is given a low weighting.

Suggested Weighting	Barriers 0 No barriers 1
Massimo Civita	
Robin Herbert	Tick
Harriet Nash	
Alain Dassargues	Agree
Jaroslav Vrba	
Antonio Bosch	
Lucila Candela	
Nathalie Doerfliger	tick
Javier Temino Vela	Barriers 0 No barriers 1
Doug Kelly	
Ann Williams	Negative barriers (i.e. highly permeable layers) 3 - see comments
Revised Weighting	Barriers 0 No barriers 1 -ve barrier 3 i.e. highly permeable layer

[2.2 Comments]

Massimo Civita	I don't know if it is true with regard to fractured and Karstic ??? The exposed section value is very important
Robin Herbert	
Harriet Nash	But? more likely to have barriers if the aquifer is thin.
Alain Dassargues	Difficult to answer - see remark of 1.2
Jaroslav Vrba	Thickness of significant number of shallow aquifers in Central Europe is less than 30 m.
Antonio Bosch	
Lucila Candela	Most of our aquifers are even thinner.
Nathalie Doerfliger	
Javier Temino Vela	
Doug Kelly	
Ann Williams	In a very thin aquifer it might not be possible to have significant ground water level decline at abstraction points to cause saline intrusion.
Revision	

2.2 Aquifer Thickness - I2

Notes: The thinner the aquifer the greater the susceptibility.

Suggested Weighting **m**	<50 50 - 100 >100	3 2 1
Massimo Civita	<50 50 - 100 >100	3 2 1
Robin Herbert	Tick	
Harriet Nash		
Alain Dassargues		
Jaroslav Vrba	<30 30 - 100 >100	3 2 1
Antonio Bosch		
Lucila Candela	<25 25 - 100 >100	3 2 3
Nathalie Doerfliger	OK	
Javier Temino Vela	<25 25 - 100 >100	3 2 1
Doug Kelly		
Ann Williams		
Revised Weighting	<30 30 - 100 >100	3 2 1

[2.1 Comments]

Massimo Civita	Mind intermittent or seasonal pumping Use monthly mean
Robin Herbert	
Harriet Nash	Upconing seems to be as much a problem as 'lateral' intrusion - e.g. the Campanian Plain; may be from sea water or old/connate water - not sure that hydraulic gradient is so significant and what do you take? - general gradient or gradient between sea and pumping levels. Negative gradient? only produced by pumping. Problems with transient state and many areas already subject to intrusion.
Alain Dassargues	
Jaroslav Vrba	Hydraulic gradient towards the coast is considered in dynamic stage (under the influence of groundwater of groundwater pumping) or on a steady - stage flow (groundwater system is not exploited). I think that the influence of hydraulic gradient on saline intrusion susceptibility is bigger than aquifer thickness.
Antonio Bosch	Only coastal aquifers?
Lucila Candela	
Nathalie Doerfliger	Do we consider the natural or the influenced gradient due to pumping for water supply? Maybe the information about the Q of pumping should be taken into consideration as a qualifier?
Javier Temino Vela	
Doug Kelly	
Ann Williams	Distance from the coast might be considered
Revision	

2 Susceptibility to saline intrusion

Susceptibility to saline intrusion: I = I1 + I2 + I3
Qualifier relating to the rate of occurrence: Iq = I4

2.1 Hydraulic Gradient towards the coast - I1

Notes: if there is no adjacent body of saline water then there is no susceptibility to saline intrusion.

Suggested Weighting	Strongly positive Generally zero Strongly negative		0 1 3	
Massimo Civita	+ 0 -		0 1 3	
Robin Herbert	+ 0 -		0 3 6	 SI certain SI occurring
Harriet Nash				
Alain Dassargues	+ + - -	$> 1:10^{-3}$ $1:10^{-3} - 0$ $0 - -1:10^{-3}$ $< -1:10^{-3}$	0 1 3 5	
Jaroslav Vrba	+ 0 -		0 1 4 or 5	
Antonio Bosch				
Lucila Candela				
Nathalie Doerfliger	Positive 0 Negative		1 2 4	
Javier Temino Vela	Positive 0 Negative		0 1 3	
Doug Kelly	Strongly Positive Generally Zero Strongly Negative		-1 5 NA	
Ann Williams	Positive 0 Negative		0 2 4	
Revised Weighting	Strongly Positive Generally Zero Strongly Negative		0 3 5	

[1.3 Comments]

Massimo Civita	Net recharge may be higher than 200 mm/y but very concentrated
Robin Herbert	OK
Harriet Nash	How would this be distributed areally? Presumably confined aquifer = 6, regardless of recharge in unconfined part; but what about leakage? - may be too simplistic
Alain Dassargues	
Jaroslav Vrba	In Central European conditions the range of the recharge 50-200 mm/year is too big, the some the limit 200 mm. See my proposal on the table 1.3. Question: why do you start in the tables 1.I and 1.2 in the scale of weight from bigger values to smaller one, and in case of table 1.3 the scale of the values of the weight is reversed?
Antonio Bosch	Seems OK to me…due to the influence of the limits and the natural evolution of piezometric levels, which could be of interest is a parameter which takes it into account, be it by the distance to the impermeable boundaries or by the total area of the system
Lucila Candela	Difficult to be applied in arid zones.
Nathalie Doerfliger	Recharge = effective infiltration after having subtracted the evaporation, evapotranspiration in the water balance. OK That means that recharge is the more important factor on the general value of the susceptibility to groundwater decline. Certainly it's correct. *upgrading this value and keeping the susceptibility limit value for the 3 degrees, this H3/2 has a strongest influence _ pessimistic and safest case. Why didn't you take into consideration the unsaturated zone thickness? I do think it has an influence on the groundwater level decline, specificalyy, is this zone thick or not? Large value _ greater weight Don't you think it should be important to consider the interaction between surface water and groundwater? Is it included in the attribute H3?
Javier Temino Vela	I suggest you consider the possibility of including another aspect (H4) with equal weight to recharge: "potential use of aquifer". An aquifer with "high potential use" is that which can provide high extractions at low cost. The aquifers are very susceptible to "overexploitation" An aquifer with "low potential use" is that which can provide low abstractions at high cost. Not very susceptible to "overexploitation" The rest are aquifers of "moderate potential" - see attached paper.
Doug Kelly	
Ann Williams	
Revision	

1.3 Recharge - H3

Notes: Recharge to watertable, not precipitation.

Suggested Weighting **mm/year**	>200 50 - 200 <50	1 3 6
Massimo Civita	>500 300 - 500 200 - 300 50 - 200 <50	1 2 5 7 9
Robin Herbert		
Harriet Nash		
Alain Dassargues	>200 100 - 200 50 - 100 <50	1 2 3 6
Jaroslav Vrba	>150 50 - 150 <50	1 3 6
Antonio Bosch		
Lucila Candela	Is 6 correct?	
Nathalie Doerfliger	>200 50 - 200 <50	1 4 * 6
Javier Temino Vela	>200 50 - 200 <50	1 3 6
Doug Kelly		
Ann Williams		
Revised Weighting	>200 100 - 200 50 - 100 <50	1 2 3 6

[1.2 Comments]

Massimo Civita	Mind the nature of the layers and their thickness. I think it must be specified: eg. >10 layers (fine grained)/50m
Robin Herbert	Not important
Harriet Nash	
Alain Dassargues	Cannot be oversimplified like that - in reality the susceptibility to groundwater level decline in such a layered system depends in each case, on many factors and parameters.
Jaroslav Vrba	In central European conditions (Germany, Poland, Czech Republic, Slovakia, Austria, Hungary and Slovenia) the thickness of the first shallow non-consolidated aquifer in fluvial and glacio-fluvial deposits is mostly less than 50 m. I propose to avoid the limit 50 m. I must be defined what we consider as a layer. Minimum thickness and areal extension has to be defined. I do not think that aquitards with the thickness 3-5 cm and areal extension 50-100 m^2 which are frequently developed in shallow aquiffers in fluvial deposits in river terasses in Central Europe are the layers, which will be calculated in the frame of heterogenity (1.2). I propose that total (cumulative) thickness of aquitards will be expressed in relation to the total thickness of the aquifer. Example: thickness of aquifer: 25 m, total thickness of three layers of aquitards: 5 m; 20% of total thickness of aquifer is composed by impermeable material. More important is how thick are the layers, than how many there are.
Antonio Bosch	
Lucila Candela	I find more appropriate the alternative deffinition. It is difficult to evaluate number of layers per 50 m of aquifer, especially when dealing with small sedimentary basins.
Nathalie Doerfliger	What about considering the heterogeneity either as mentioned above for multilayer aquifers or density of fractures per log-metre? - requirement of boreholes! How do we take into consideration the permeability of each layer particularly for aquifers with layers of confining material? Is it only for porous media aquifers or also for fissured and karstic aquifers?
Javier Temino Vela	What is "0 layers/50m"? I suggest you use the whole aquifer thickness and a parameter which indicates the no of aquifer layers and a median thickness eg: $\frac{\text{No. aquifer layers}}{\text{Total no. layers}} \times \frac{\text{thickness of aquifer layers}}{\text{total thickness}}$
Doug Kelly	
Ann Williams	
Revision	(Total thickness) / (total thickness of aquifer layers)

1.2 Vertical Heterogeneity - H2

Notes: This parameter is the number of layers per 50 m thickness of aquifer (or should it be the overall total number of layers?)

Suggested Weighting **layers/50 m**	1 1 2 - 10 2 >10 3
Massimo Civita	OK
Robin Herbert	
Harriet Nash	
Alain Dassargues	
Jaroslav Vrba	
Antonio Bosch	
Lucila Candela	
Nathalie Doerfliger	OK for multilayer porous media or porous and karstic or fissured. For fissured / karstic:- Epikarst and karst network 3 Intermediate well-developed case 2 Fissured but "homogeneous" 1
Javier Temino Vela	2 1 3 - 10 2 >10 3
Doug Kelly	
Ann Williams	
Revised Weighting	1 1 2 - 10 2 >10 3

[1.1 Comments]

Massimo Civita	The middle class is too wide (Sorry for DELPHI)
Robin Herbert	$Re = 1.5 (T t / S)^{-2}$ - radius of influence after t with no recharge! See Herbert and Adams N.b. For 6 monthly dry period: t = 180 days, for T = 100 $S_{unconfined} = 1$, T/S = 1000, Re = 400 m
Harriet Nash	OK - confined is 3; unconfined is 1 I like the use of diffusivity - good for area with artesian flow
Alain Dassargues	Seeing units (m^2/d) I suppose that hydraulic diffusivity is transmissivity (i.e. hydraulic conductivity and saturated thickness). May I suggest that the overwhelming parameter which influences the susceptibility to groundwater level decline is the storage coefficient and not the hydraulic conductivity. If "hydraulic diffusivity" is the ratio Transmissivity/storage, I agree globally with the suggestion.
Jaroslav Vrba	
Antonio Bosch	
Lucila Candela	I find 50000 too high
Nathalie Doerfliger	Is it an average value for a multilayered aquifer? Is this transmissivity resulted from the average ?? weighted by the thickness of each layer?
Javier Temino Vela	Diffusivity is not known for the majority of Spanish aquifers. I think it would be better to substitute a better known parameter, this would make the method more easily applicable.
Doug Kelly	
Ann Williams	Hydraulic Diffusivity may be the "correct" parameter but it is not in common usage. If it is to be used it should be defined (T/S). Also for a given diffusivity the drawdown varies significantly with transmissivity - $s=QW(u)/4\Pi T$, $u=r^2S/4tT$, u is dependent on S/T while s is dependent on u and T.
Revision	Note the discrepancy between Herbert's values and Civita's comments. Are four weighting bands too many?

1 Susceptibility to groundwater level decline

Susceptibility to groundwater decline: H = H1 + H2 + H3

1.1 Hydraulic Diffusivity - H1

Notes: Equivalent to Transmissivity / Storage Coefficient.

	Range	Weight	
Suggested Weighting **m²/day**	>50,000 10,000 - 50,000 <10,000	3 2 1	
Massimo Civita	>50000 30000 - 50000 10000 - 30000 <10000	4 3 2 1	
Robin Herbert	>1,000,000 >100,000 <10,000	3 2 1	
Harriet Nash			
Alain Dassargues	Agree		
Jaroslav Vrba	Agree		
Antonio Bosch			
Lucila Candela	>10000 5000 - 10000 <5000	3 2 1	
Nathalie Doerfliger		3 2 1	
Javier Temino Vela	>50 10 - 50 <10	3 2 1	(>50,000 assumed)
Doug Kelly			
Ann Williams			
Revised Weighting	>75000 30000 - 75000 10000 - 30000 <10000	4 3 2 1	

General Comments

Massimo Civita	Abstract on DRASTIC attached
Robin Herbert	Extract from Terzaghi & Peck attached
Harriet Nash	I'm not clear how these indices can be applied in practise
Alain Dassargues	
Jaroslav Vrba	
Ing. M.J.Villasuso Pino*	I hope that these comments to your work will be useful to the final adopted criteria. My experience is limited to karstic environments. Susceptibility to these aquifers is worked this year here in the Yucatan aquifer by Dr. Ben Klink, a good friend of mine. Give to him my greetings, as well as to Brian Morris, David Buckley, and Stephen Foster.
Mr Andrew Ezzy *	At present I am working on the groundwater resources of southern Tasmania. The island on the south eastern corner of Australia. This seems a little above me at the moment. Though give me a week or two and I'll send you my completed copy. Please feel free to send me any information on recent work into diagnostic methods on groundwater resources.
Antonio Bosch	
Lucila Candela	I have tried to answer your questionnaire although I sometimes found it difficult to understand. However it is a good idea to prepare such a tool. I hope you have great success.
Nathalie Doerfliger	
Javier Temino Vela	
Doug Kelly *	The focus of my work (beginning about 1 year ago) is primarily sea water intrusion. As a result I'm very interested in your work. Please keep me advised, and feel free to contact me if I may be of assistance.
Michel Bakalowicz *	One needs to ask if the aquifer under consideration is permeable, fissured or karstic. The method is not applicable to karstic environments.
Ante Sarin *	Do not add the three indecies together, the three factors are "cousins" not "brothers". They could be usefully shown on a map. Also suggests use of groundwater surplus factor - i.e. rising water levels.
Ann Williams	Questionnaire was difficult to fill in. The major problem seems to be in deciding which parameters should be used for the main aquifer property T, T/S etc. Graph attached shows how drawdown changes with T and T/S for a range of S values.

** These respondents provided general comments only and did not provide written additions/comments to the remaining tables.*

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	Index of susceptibility to groundwater decline for various aquifer attributes			
	Hydraulic diffusivity	*Heterogeneity*	*Annual recharge*	*Volume of aquifer*
High	3	3	1	1
Moderate	2	2	3	2
Low	1	1	6	3

Table 1. A method for estimating the susceptibility of an aquifer to groundwater decline using four aquifer attributes. Three different score bands for the sum of the indices are suggested: < 8, 8-11, and > 11, denoting slight, significant and grave susceptibility to water-level decline.

	Index of susceptibility to saline intrusion for various aquifer attributes		
	Hydraulic gradient towards the coast	*Permeability*	*Effectiveness of hydraulic barriers*
High	1	3	1
Moderate	2	2	2
Low	3	1	3

Table 2. A method for determining the susceptibility of an aquifer to saline intrusion using three aquifer attributes. Three different score bands for the sum of the indices are suggested: < 5, 5-7, and > 7, denoting slight, significant and grave susceptibility to saline intrusion. The technique assumes there to be a source of saline water near to the exploited aquifer.

	Index of susceptibility to subsidence for an unconsolidated aquifer		
	Stratification of aquifer	*Combined thickness of aquitards*	*Compressibility of aquitards*
High	3	3	3
Moderate	2	2	2
Low	1	1	1

Table 3. A method for estimating the susceptibility of an unconsolidated aquifer to subsidence. The three different score bands for the sum of the indices are suggested: < 5, 5-7, > 7, again denoting slight, significant and grave susceptibility to subsidence. N.B. if the aquitard compressibility can not be estimated then aquifer stratification and aquitard thickness only should be estimated and score bands of <3, 3-5, <5 be used.

N.B. In the above tables, weighting of the separate aquifer attributes is implicit in the scoring system used - see particularly *Annual Recharge* in Table 1. However, future work will need to identify explicit weighting and also specific limits for the *High Moderate and Low* ranges of the separate attributes to facilitate widespread application of the methodology leading to inter-regional comparison of aquifer susceptibility - see Conclusions.

Administration as part of their Technology Development and Research Programme (Adams & MacDonald, 1995). This paper is published with the permission of Director, British Geological Survey, National Environment Research Council.

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groundwater level decline must also precede saline intrusion and/or subsidence, it is recommended that for any aquifer the susceptibility to water level decline is quoted first and is qualified by the other two.

As an example of the use of the tables, consider Table 1. An aquifer with high *Hydraulic Diffusivity* (3), low *Heterogeneity* (1), low *Annual Recharge* (6), and a small *Volume* (3) will have an overall index of susceptibility to groundwater decline of 13, and thus be deemed to have **grave susceptibility to groundwater decline.**

CHRONOLOGY

It would be extremely convenient if each excessively exploited aquifer followed the same pattern of degradation. Unfortunately this is not the case. Some aquifers are more susceptible to subsidence than saline intrusion, others will experience saline intrusion after only a small decline in water-levels, and still others can experience severe dewatering without any decrease in quality or subsidence. The chronology of the impacts of exploitation depends critically on the unique conditions of individual aquifers.

Once the susceptibility of an aquifer to the three different impacts of exploitation has been determined a more coherent chronology can be proposed. For example, if an aquifer is gravely susceptible to subsidence, but only slightly susceptible to saline intrusion, then it is reasonable to expect that subsidence will occur first; i.e. detrimental effects having the higher rating are likely to happen first.

Generally, however, groundwater-level decline is required to occur before any other detrimental effects can develop. Only after water-levels have declined sufficiently will the hydraulic gradients be reversed allowing saline water to contaminate the aquifer. Likewise, water-levels have to decrease to allow leakage from the aquitards and therefore consolidation and subsidence. As a general rule, therefore, water-level decline will occur first followed by either saline intrusion or subsidence depending on the susceptibility of the aquifer to both.

The effect of water-level decline can often manifest itself in different ways. In the first instance, there can be a general decrease in water-levels, rendering pumping from abstraction boreholes less efficient. This may be followed by reduction of surface discharges, including springs or rivers drying up or the drainage of wetlands. After all these surface discharges have been eliminated, water-levels can continue to decline leading to other detrimental effects. It follows that falling water levels in the aquifer (not in pumped boreholes) are a warning to developers that further, more serious degradation might follow.

CONCLUSIONS

A first step in the development of a diagnostic approach to the determination of aquifer susceptibility to exploitation side-effects (**aquifer susceptibility**) has been presented. In its current form the methodology should be seen as a first step in the development of an approach with potential for wide application as a planning and management tool. As such it should only be used with great caution for inter-regional comparisons of aquifer susceptibility .

In order for the methodology to become widely applicable a significant effort must be made to develop specific weights for the individual parameters used in Tables 1-3 and specific ranges for the current relative designations of *High, Moderate* and *Low*. One way in which this could be achieved is by application of scaling techniques and the Delphi procedure (Dee *et al.* 1973) - this approach is currently being considered by the authors in a research project funded by ODA.

Further potential for development of the method is provided by current research being carried out by the British Geological Survey and the Natural Resources Institute (UK). This study is considering the interdependency of hydrogeology and socio-economic factors in groundwater resources degradation and the mitigation of the impacts of such degradation. In the future it may be possible to add socio-economic considerations to the diagnostic approach.

The separate elements of the approach described in this paper contain nothing new for the practising hydrogeologist. However, the combination of these elements provides a diagnostic methodology which is accessible to the non-hydrogeologist, and as such can provide an important element in the general planning process. The authors envisage that, in certain circumstances, the methodology can be as useful to planners as the concept of aquifer vulnerability to pollution and future developments could include the production of aquifer susceptibility maps. It is will probably find most application in regions having rapidly developing economies which are highly dependent upon groundwater.

ACKNOWLEDGEMENTS

The concepts discussed in this paper were developed during a project financed by the British Overseas Development

Groundwater Quality

The abstraction of significant amounts of groundwater can lead to the deterioration of water quality within an aquifer by such means as induced contaminant flow resulting from a new hydraulic head distribution; saline intrusion; and geochemical evolution of groundwater.

The aspect of induced pollution is directly related to consideration of aquifer vulnerability to pollution. As evaluation of aquifer vulnerability has been widely discussed elsewhere (Adams & Foster, 1992; Vrba & Zaporozec, 1994), it is not included in this discussion. Indeed, the authors believe that the concept of aquifer susceptibility to exploitation side-effects will become a "tool" similar to that of aquifer vulnerability to pollution.

Saline intrusion is an important consideration for aquifers adjacent to the sea or other saline water bodies. The mobility of such saline water depends upon the local hydraulic gradients (enhanced by groundwater abstraction), the permeability of the aquifer and the presence or otherwise of hydraulic barriers. As with the discussion of declining water levels, a consideration of the time period involved in movement of a saline front is important; movement over a few years would normally be a matter of concern, indicating a high susceptibility to the side effects of exploitation, but movement over hundreds or thousands of years could well be acceptable in the context of long-term management strategies.

Upconing of deeper saline water can also be a problem; groundwater abstraction can disrupt an existing hydraulic regime beyond a critical point resulting in upconing of saline water into the exploited aquifer (Schmorak & Mercado, 1969; Miroshnikov, 1973).

Another way in which the intrusion of water with dissimilar hydrochemistry can affect an aquifer is to alter the physical properties of the aquifer. These physical changes can manifest themselves in changes in porosity and permeability and result from diagenetic processes brought about by water-rock interaction (Goldenburg *et al.* 1986). Such processes can be non-reversible and irrevocably damage the fabric and hydraulic properties of the aquifer.

Changes induced in the groundwater hydrochemistry due to water-rock reaction may also have detrimental health implications when the aquifer concerned is used for potable supply. One extreme example is that of arsenic and its deposition from or solution in groundwater in certain environments, depending on the local redox conditions (e.g. Korte, 1991). Under natural conditions, all aquifer systems undergo redox changes as groundwater moves along flow lines. Timescales of redox change vary widely, the main control being the nature of the aquifer (amounts of reducing constituents: organic carbon, reduced iron, sulphide). Thus redox processes may be more rapid in marine argillaceous sediments than in red bed sandstones for example (Edmunds *et al.* 1984; Edmunds, 1994). However, whilst groundwater exploitation greatly enhances flow rates, study has shown that redox zones (as well as other hydrochemical zones) are comparatively stable during quite drastic changes in the groundwater regime (Edmunds *et al.* 1984). Thus it is felt that development of diagnostics of susceptibility which involve a consideration of changes in quality as a result of movement of redox boundaries is not likely to be helpful.

A FIRST STEP IN THE DEVELOPMENT OF DIAGNOSTICS

In the preceding sections various physico-chemical parameters which affect the susceptibility of an aquifer to exploitation side-effects have been discussed. This section combines some of these contributing factors to formulate a set of diagnostics to determine aquifer susceptibility to excessive exploitation. Necessarily only a rough guideline can be given since the many idiosyncrasies unique to particular locations cannot be accounted for; used critically however, a general guideline can be a useful tool for giving a first estimate of such susceptibility.

As the side-effects resulting from aquifer exploitation can involve a variety of detrimental impacts, it was thought expedient to establish three scales of susceptibility which relate to groundwater level decline, saline intrusion and subsidence, respectively. This approach is considered to be more pragmatic than having a single measure of susceptibility which would necessarily involve a large number of interactive variables. Groundwater pollution in its general sense is not included as this is dealt with elsewhere under a consideration of aquifer vulnerability to pollution.

The technique is based on assigning numerical values to each of up to four aquifer features relevant to groundwater level decline, saline intrusion or subsidence, and then summing to give an overall grade of susceptibility to the particular impact of exploitation under consideration. For each factor three grades are possible, high, moderate or low (Tables 1, 2, 3). Once the grades have been determined Tables 1, 2 and 3 can be used to attribute numbers for each parameter. As only relative values are used in the separate grading tables, the diagnostics as presented cannot be used for inter-regional comparisons - future work will need to establish ranges and weights for the separate parameters (see Conclusions). Equally, the method can not be used for absolute assessment of the effects in detail. Users on a regional scale however will develop their own perception of the grading as their experience in application of the method increases. As

Participants of a recent International Association of Hydrogeologists' Congress on the topic (Simmers *et al.* (Eds) 1992) and an associated workshop concluded that while the concept of overexploitation was useful in "Public Relations" terms, it was incapable of precise definition. In these circumstances care needs to be taken in the use of the word - hence, its use in this paper has generally been avoided.

Evidently where excessive or irrational aquifer exploitation results in a range of differing impacts, some consideration of the collective "result" should be made. Thus, a consistent means of evaluating the advantages and disadvantages of any particular groundwater development plan is required which is capable of equating the benefits provided by the use of the exploited water with any "undesirable" impacts such exploitation may have. Potential for such an approach lies within economic analysis (e.g Young, 1992).

INDICATORS OF EXPLOITATION SIDE EFFECTS

As noted previously, "overexploitation" is generally only diagnosed *a posteriori*, and discussion of many examples from various parts of the world can be found in the literature (e.g. Pulido Bosch *et al.* 1989; Simmers *et al.* 1992). From a general review of the literature it is evident that exploitation can result in a variety of side-effects depending on the degree or scale at which it has occurred. The main effects which can result from excessive or irrational development include: reduction in piezometric levels, land subsidence and deterioration of water quality.

Groundwater-level Decline

It is common for "overexploitation" to be defined as the condition which exists when total groundwater abstraction exceeds the recharge, giving rise to significant groundwater-level decline. However, all aquifers, whether excessively exploited or not, experience some degree of water-level decline as a response to any degree of groundwater abstraction. When recharge is greater than abstraction a transition state (during which water levels will decline) will always occur between the onset of pumping and a subsequent steady-state (when water levels stabilise). The length of this transition period depends upon a number of factors including the magnitude of the difference between recharge and abstraction, and intrinsic parameters of the aquifer (Custodio, 1992). It is therefore important to consider at what stage these falling water-levels become serious and what level of drawdown is acceptable; this is a decision which ideally should be based on consideration of both the physical and socio-economic consequences of water-level decline. Evidently in many situations "unacceptable" drawdown can occur, even when recharge exceeds the total groundwater abstraction; environmental impacts, such as dewatering of wetlands and reduction of river flows can be particular manifestations of declining groundwater levels in certain situations.

Land Subsidence

As the thickness of sedimentary deposits build up during the process of deposition, the increasing weight of the overburden compresses the underlying strata. At each stage, the system tends towards equilibrium where the weight of the overburden is balanced by the effective intergranular stress in the skeleton of the formation in combination with the pore water pressure. Groundwater abstraction has the effect of decreasing the pore water pressure thus increasing the effective stress from the overlying strata on the aquifer's matrix. When the increase in effective stress is greater than a critical value (the preconsolidation stress) the resulting compaction of the sediments is mainly inelastic and therefore not recoverable.

Dewatering of any unconsolidated sedimentary strata leads to an increase in effective stress upon the matrix. However, coarse-grained sandy aquifer strata form a rigid matrix skeleton which generally resists compaction whereas finer-grained clayey strata are more compressible and hence, more prone to compaction. Where relatively coarse-grained aquifers are bounded by fine-grained aquitards, groundwater abstraction from the coarse layers can induce leakage from the aquitards; the resulting delayed dewatering of the aquitards can result in greater compaction than that of the aquifer. Thus in a multilayered system consisting of coarse-grained aquifer separated by clayey aquitards, cumulative compaction of the aquitard layers can result in significant subsidence at the ground surface.

During the compaction process a state can be reached where the porosity of the original material is reduced to a point beyond which no significant future compaction will occur. The term "stable depth" has been used to define the point at which the weight of the overburden corresponds to the loading required to achieve this state (Prokopovich, 1976). Thus, stable and unstable fields can be defined as occurring below and above the stable depth respectively. In areas where erosion processes remove portions of the uppermost "unstable" strata, the potential for subsidence is reduced. Conversely subsidence is more probable in areas of deposition in which the entire thickness of the more "unstable" section is preserved. This consideration has not been explicitly included in the diagnostic approach presented in this paper but is worthy of future consideration.

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AQUIFER SUSCEPTIBILITY TO SIDE-EFFECTS OF GROUNDWATER EXPLOITATION

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ABSTRACT

Aquifer vulnerability has become a "cornerstone" of groundwater protection policies, taking into account as it does aspects of pollution resulting from applied contaminant load. However this is not the whole story and groundwater resource degradation can also result from other impacts of development such as piezometric level decline, saline intrusion and subsidence. It is generally the case that such impacts are normally diagnosed after they have occurred. Nevertheless it is evident that certain aquifers are more susceptible to these impacts (often referred to as "overexploitation") than others.

As a first step towards a method to determine aquifer susceptibility to such impacts, a diagnostic method is introduced as a means to provide managers and planners with an additional method of evaluating potential aquifer degradation as a result of development.

The method as presented is at an early stage of development and cannot yet be used for inter-regional comparisons. Used critically, however, the authors believe it provides a useful tool for giving a first estimate of aquifer susceptibility. Planned future developments of the methodology are also presented.

INTRODUCTION

"Aquifer and groundwater overexploitation is a relatively new, ambiguous and controversial concept in Hydrogeology" (Custodio, 1992), and its effects are being increasingly reported in the literature (e.g. Simmers *et al.* (Eds) 1992, Pulido Bosch *et al.* (Eds) 1989). Given that "overexploitation" and, hence, its various impacts are widespread, some measure of the susceptibility of aquifers to this effect would be useful. If the potential impacts of excessive exploitation can be identified before they occur, or at least before they become significant, then management measures can be taken to avoid or mitigate their worst effects.

In themselves, the component parts of the diagnostic method discussed in this paper present nothing new to the practising hydrogeologist. However, the authors believe that the integration of these parts has several benefits, mainly:

1) It facilitates the development of a conceptual model of a region or system using concepts already available to hydrogeologists, and helps identify the hydrogeological factors important in determining resource sustainability.

2) It provides a tool to planners responsible for regional development to enable them to assess (in broad terms) the long-term inter-relationship between such development and the regional groundwater resources.

The purpose of this paper is to present an initial step to a widely applicable methodology and to initiate discussion of the potential of such a "tool". For example, the concept of susceptibility could be developed in the same manner, and be as useful as that of vulnerability to pollution. The term **susceptibility** is used to avoid confusion with the term **vulnerability**, which is now generally used specifically in the context of pollution (Adams & Foster, 1992; Vrba & Zaporozec, 1994). An indication of further work required in the development of this approach is also given.

CONCEPT OF OVEREXPLOITATION

The concept of aquifer overexploitation is one that is poorly defined, is possibly incapable of definition (Foster, 1992) and, because a full hydrogeological assessment is generally only possible after an aquifer has been stressed, is normally only diagnosed after it has occurred. A number of terms have been used in the literature over the years to convey the concept (Adams & MacDonald, 1995) but close examination shows that there is possibly no one suitable generic term. In general, definitions of overexploitation tend to depend on a concept of "undesirable results"; however this will be perceived differently by the exploiter, an affected third party, the licensing authority, and environmentalists. Thus overexploitation is a relative concept dependent upon the criteria used to define it: qualitative, economic, social, ecological etc.

Susceptibility to subsidence (continued)

Rate of occurrence qualifier - S_q
The rate at which an aquifer compresses depends on how fast the aquitards dewater. This depends on the thickness of individual layers of aquitard and their permeability. Having included the total thickness of aquitard in table 3.1, table 3.3 allows estimation of the number of individual layers (which implicitly gives the average thickness of aquitard), and table 3.4 allows estimation of the permeability. It is proposed that these two factors should be added together and used as qualifiers to the susceptibility to subsidence. For example a particular aquifer system may be highly susceptible to land subsidence, the full effects of which may not become apparent for a number of decades (i.e a low rate).

3.3 Number of layers - S_3

Suggested values	
Range	Weight
11 - 100	3
10 - 2	2
1	1

Range	Weight

Comments

3.4 Permeability of aquitard - S_4

Suggested values	
Range	Weight
> 10 m/day	3
10 - 10^{-3} m/day	2
< 10^{-3} m/day	1

Range	Weight

Comments

3. Susceptibility to subsidence

Aquitards are usually more compressible than aquifers. The amount an aquifer can compress per unit drop in head is believed to be proportional to the compressibility and the thickness of the aquitards.

N.B. Some considerations related to Risk which could be added as qualifiers:
(i) A low transmissivity will give a deeper cone of depression of lesser aerial extent - more prone to differential subsidence which can have a greater economic impact than regional subsidence.
(ii) Is it an urban or rural environment?
(iii) Are there surface water considerations ? - Risk of flooding.

3.1 Compressibility of aquitards - S_1 (NB 1 Pa = 1 N/m^2 = 1 kg m^{-1} s^{-2})

Suggested values	
Range (Pa^{-1})	Weight
$\geq 10^{-6}$	3
10^{-6} - 10^{-8}	1
$< 10^{-8}$	0

Range	Weight

Comments

3.2 Combined thickness of aquitards - S_2

Suggested values	
Range (m)	Weight
>25	3
10 - 25	2
0 - 10	1

Range	Weight

Comments

Susceptibility to saline intrusion (continued)

2.3 Effectiveness of barriers - I_3

Suggested values	
Range	Weight
No barriers	1
Barriers	0

Range	Weight

Comments: This factor allows for the presence or absence of a barrier(s) preventing saline intrusion. As it will not always be obvious, this factor is given a low weighting (i.e. 0 or 1).

Rate of occurrence qualifier - S_q

The rate at which saline intrusion occurs depends on the aquifer permeability. Permeability does not affect the eventual scale of the saline intrusion and so I_4 is used as a qualifier.

2.4 Permeability of aquitard - S_4

Suggested values	
Range	Weight
>10 m/day	3
10 - 10^{-3} m/day	2
< 10^{-3} m/day	1

Range	Weight

Comments

2. Susceptibility to saline intrusion

N.B. Evidently, if there is no adjacent body of saline water then the system can not be susceptible to saline intrusion.

2.1 Hydraulic Gradient towards the coast - I_1

Suggested values	
Range	Weight
positive	0
0	1
negative	3

Range	Weight

Comments: Negative means strongly -ve. Positive means strongly +ve. 0 means generally flat.

2.2 Aquifer thickness - I_2

Suggested values	
Range	Weight
<50m	3
50 - 100m	2
>100m	1

Range	Weight

Comments: The thinner the aquifer the greater the susceptibility.

Susceptibility to groundwater level decline (continued)

1.3 Recharge - H_3

Suggested values	
Range (mm/year)	Weight
> 200	1
50-200	3
< 50	6

Range	Weight

Comments: N.B Recharge **NOT** precipitation.

1. Susceptibility to groundwater level decline

1.1 Hydraulic Diffusivity - H_1

Suggested values	
Range (m^2/day)	Weight
> 50,000	3
10,000 - 50,000	2
< 10,000	1

Range	Weight

Comments

1.2 Heterogeneity - H_2

Suggested values	
Range	Weight
>10 layers/50m	3
1 - 10 layers/50m	2
0 - 1 layers/50m	1

Range	Weight

Comments: This parameter is a measure of the number of layers per 50m of aquifer. An alternative measure could be the number of identifiable layers of the total thickness of aquifer being considered. Your comments welcomed.

KEY TO THE QUESTIONNAIRE'S TABLES

Susceptibility to groundwater decline $H = H_1 + H_2 + H_3$

Weight	Factor	Table
H_1	Diffusivity	1.1
H_2	Heterogeneity	1.2
H_3	Recharge	1.3

Susceptibility to saline intrusion $I = I_1 + I_2 + I_3$
Qualifier relating to the rate of occurrence $I_q = I_4$

Weight	Factor	Table
I_1	Hydraulic gradient towards coast	2.1
I_2	Aquifer thickness	2.2
I_3	Effectiveness of barriers	2.3
	QUALIFIER	
I_4	Permeability	2.4

Susceptibility to subsidence $S = S_1 + S_2$
Qualifier relating to the rate of occurrence $S_q = S_3 + S_4$

Weight	Factor	Table
S_1	Compressibility of aquitards	3.1
S_2	Combined thickness of aquitards	3.2
	QUALIFIERS	
S_3	Number of layers	3.3
S_4	Permeability of aquitard	3.4

In the tables that follow we have given suggested ranges and weights for the different parameters involved in the shaded section on the left of the page. On the right hand side of the page are blank tables for you to put what you consider are the most appropriate ranges and weights for each parameter. If there are other factors which you think should be included, please indicate these in the COMMENTS section.

AQUIFER SUSCEPTIBILITY DIAGNOSTICS QUESTIONNAIRE

The diagnostic method of Adams and MacDonald (1995 - copy attached) contains nothing new for the practising hydrogeologist, it is the integration of the various component parts of the methodology which is novel. During the preparation of this questionnaire, some developments in the methodology presented in the attached paper have occurred.

The approach adopted uses three indices H, I and S, to represent the susceptibility of an aquifer to groundwater decline, saline intrusion and subsidence respectively. Thus the susceptibility of an aquifer depends on each index as shown:

Susceptibility	Groundwater decline	Saline intrusion	Subsidence
Slight	$H < 5$	$I < 3$	$S < 2$
Significant	$5 < H < 8$	$3 < I < 5$	$2 < S < 3$
Severe	$8 < H$	$5 < I$	$3 < S$

Each index is calculated by summing a number of weights; the value of each weight depending on certain factors.

It is now proposed that Susceptibility should be expressed as susceptibility to groundwater level decline (using the tables in 1, following). This evaluation can then be qualified, if appropriate, by reference to the susceptibility to saline intrusion and/or land subsidence (using tables 2 and 3 respectively).

Some factors in the determination of susceptibility to saline intrusion and land subsidence relate to the rate at which these effects occur rather than the severity or magnitude of the occurrence. These factors (e.g. permeability) should therefore be used to provide qualification to the main statement of susceptibility e.g:

> *The aquifer system under consideration is susceptible to groundwater decline with no likelihood of saline intrusion but severe susceptibility to land subsidence, the full effects of which may not be seen for a significant period of time.*

We realise that there are many demands on your time and do not wish to add unnecessarily to those; **we would therefore suggest that your first intuitive response might be more valuable than a time consuming detailed evaluation.**

When we have received the responses to this circular we will analyse them and inform you of the result. At that stage we will ask you if you would wish to modify your initial response in the light of the consensus opinion; this is essentially the Delphi method[2]. Following receipt of the second round of responses we will then publish the results. Our final report to ODA will acknowledge all those who responded (unless they specifically request otherwise). We envisage that the resulting publication will be an initial step in the development and application of the methodology. It will be further refined and modified in the future as it becomes more widely used, in a similar way to which DRASTIC has been developed and adapted for different regional applications.

If you with to provide more detailed comments or some more general observations, we would of course be pleased to receive them.

Thanking you in anticipation for your assistance which is very much appreciated,

Yours faithfully,

Brian Adams Alan MacDonald

enc:

[2] Benaire M. 1988. Delphi- and Delphilike approaches with special regard to environmental standard setting. Technological Forecasting and Social Change 33, (Elsevier) pp 149-158.

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Dear

AQUIFER SUSCEPTIBILITY DIAGNOSTICS

Firstly, yes **THIS IS A CIRCULAR**, but no we are not selling anything. Worse than that, we are asking for some help!

We are currently refining a diagnostic methodology to determine an aquifer's susceptibility to groundwater level decline and possible subsequent saline intrusion and/or subsidence. The basis of the methodology is explained in the attached short paper which was presented at the recent Applied Geoscience conference held at Warwick, UK (15 - 18 April 1996). The research is being funded by the UK's Overseas Development Administration as part of their ongoing Technology, Development and Research Programme in the Engineering sector (Water and Sanitation).

The method is an indexation technique similar to that of DRASTIC[1], with which you may already be familiar; the difference being that while DRASTIC deals with vulnerability to pollution the new method deals with the physical impacts of groundwater abstraction. The system is intended to be simple to use in that it requires minimal data and we envisage that it should be particularly useful in countries where strategic planning of groundwater resource development has yet to be undertaken; its main use will probably be by non-hydrogeologists in the general planning processes.

We wish to develop the appropriate diagnostics in a similar way to the manner in which the DRASTIC parameters were developed, i.e by expert opinion. Thus we are asking for your assistance in assessing the ranges and importance of the different parameters involved. We have enclosed three sets of tables for you to complete - one set each for water level decline, saline intrusion and subsidence. For each table we have included a grey shaded section which shows our estimates, and a white section where we would like you to fill in your estimates. In the preparation of this exercise some modifications to the method described in the Adams and MacDonald paper have been made which are explained later in the circular. There is also a space for any comments you may have - additional factors you think should have been included, reasons for deleting factors we have included etc.

---

[1] Aller L., Bennet T., Lehr J.H., Petty R.J., and Hackett G. 1987. DRASTIC: a standardized system for evaluating ground water pollution potential using hydrogeologic settings. U.S. E.P.A, EPA/600/2-8-036, 455p.

4. CONCLUSIONS

Due to the length of time taken to receive the responses it was not possible to complete the full Delphi approach to building a consensus view. Also it might be argued that the relatively small number of responses, 15 in all, does not impart a high level of confidence to the results. However, those hydrogeologists who were written to individually were selected for their depth of hydrogeological experience and, in some cases, for their particular expertise in the specific aspects saline intrusion and/or land subsidence. It is therefore felt that the results of this study are a valuable contribution to the development of this diagnostic technique.

The results now allow presentation of a more useful technique to the scientific community than that previously given (Adams and MacDonald 1997). By providing specific ranges for the individual parameters (in place of the previously general statements: High, Moderate and Low) the technique looses much of its subjectivity and thus should be available for inter-regional comparisons of aquifer development potential.

It is planned to publish the results of this study in the scientific press (possibly as a technical note) in order to make it widely available. The next stage in testing this methodology will be to apply it to a series of case studies in order to provide a more detailed validation.

5. REFERENCES

Adams B and Macdonald A M 1995. Over exploitation of aquifers - final report. BGS Technical Report WC/95/3.

Adams B and Macdonald A M 1997. Aquifer susceptibility to side-effects of groundwater exploitation. In "Groundwater Pollution, Aquifer Recharge and Vulnerability" - special publication of the Geological Society. In Press.

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Benarie M 1988. Delphi - and Delphilike Approaches with Special Regard to Environmental Standard Setting. Technological Forecasting and Social Change 33, 149-158.

TABLE 1 ***.......Continued***

S **Susceptibility to Subsidence**

S1 Aquitard Compressibility (m^2/N)

Range	Rating
$>10^{-6}$	3
$10^{-6} - 10^{-8}$	1
$< 10^{-8}$	0

S2 Combined Aquitard Thickness (m)

Range	Rating
>25	3
10-25	2
<10	1

Sq_1 Number of Layers ***Qualifyer relating to rate of occurrence*** - the more layers the quicker the impacts become evident, however, the overall scale is not affected.

Range	Rating
>10	3
2-10	2
1	1

Sq_2 Aquitard Permeability (m/day) ***Qualifyer relatiung to the rate of occurrence*** - it moderates the rate of delayed drainage and hence the compression of the aquitards, thus affecting the rate of surface subsidence but not the overall scale.

Range	Rating
>1	3
$1-10^{-3}$	2
$<10^{-3}$	1

TABLE 1 ***.......Continued***

I Susceptibility to Saline Intrusion

I1 Hydraulic Gradient towards the coast (or other saline watersource)

Range	Rating
Strongly Positive	0
Generally 0	3
Strongly Negative	5

I2 Aquifer Thickness (m)

Range	Rating
<30	3
30 - 100	2
>100	1

I3 Barrier Effectiveness

Range	Rating
Barrier(s) present	0
No barriers	1
Negative barrier (i.e. highly permeable layers)	3

Iq Permeability of Aquitard or barrier (m/day) - ***Qualifier relating to rate of occurrence*** - it moderates the rate of intrusion but does not affect the long term scale.

Range	Rating
>10	3
10^{-3} - 10	2
$<10^{-3}$	1

TABLE 1 *The revised parameter ranges and ratings tables, following the consultation process*

H Susceptibility to Groundwater Decline

H1 Ranges and Ratings for Hydraulic Diffusivity (T/S, m^2/day)

Range	Rating
> 75 000	4
30 000-75 000	3
10 000-30 000	2
< 10 000	1

H2 Ranges and Ratings for Vertical Heterogeneity (total thickness / total thickness of aquifer layers)

Range	Rating
1	1
2-10	2
>10	3

H3 Ranges and Ratings for Recharge (recharge to aquifer from precipitation in mm/yr)

Range	Rating
>200	1
100-200	2
50-100	3
50	6

if they would wish to revise their initial response in the light of the initial consensus view. The results of any such revisions would then be used to evaluate a final consensus view.

Prior to preparing the first circular, a literature review of the Delphi and other such consensus seeking approaches was carried out to establish the appropriate methodology. In broad terms it appeared that the Delphi approach as outlined above would be appropriate and had been successfully applied in development of the DRASTIC methodology, for mapping of aquifer vulnerability (Aller et al. op.cit.).

Some thought was given as to the most appropriate means of obtaining a wide enough panel of experts to achieve a meaningful consensus. The two obvious alternatives were circularising the complete membership of appropriate professional groupings (e.g. the International Association of Hydrogeologists and the Hydrogeology Group of the Geological Society) and circularising established contacts on a more personal basis in the hope of a proportionately higher response. In the end a comprise approach was adopted. Thirty-one hydrogeologists from the senior author's own network of international contacts were written to on a personal basis and the questionnaire relating to the quantification of the indices was published on the BGS Hydrogeology Group World-Wide Web site; notices about the questionnaire were posted on the 'Groundwater', 'GARNET' and 'sci.geo.hydrology' internet mailing lists - all three of which have large user communities. The circular and information provided with it are included as Appendix 1 of this report.

3. RESULTS OF THE QUESTIONNAIRE

The response rate was mixed; there were 12 postal responses to the personal letters (i.e. 39% response) and only three by e-mail in response to the World-Wide Web questionnaire. A list of respondents is given in Appendix 2. The postal responses were received fairly regularly over a period of three months which, due to the timetable of the project, precluded the provision of an initial consensus to respondents to give them the opportunity to revise their first returns. Of the postal responses received, two provided general comments on the methodology but did not return the questionnaire. The three internet respondents all provided general comments but only one provided comment on the weights and ranges, and that in only one section. Some respondents did not feel qualified to contribute to all sections and many provided useful detailed comments. A detailed summary of the responses received is given in Appendix 3.

As a result of these responses the revised tables for calculating the three indices (H, I and S) are as shown in Table 1. The number of responses received does not permit any worthwhile statistical analysis to be made but more weighting was given to the originally proposed values on the basis that a blank return may indicate general agreement. As noted earlier, under the original project programme this was to have been the initial consensus result which would then have been sent our to the original respondents to see if they wished to revise their original responses to the light of the consensus view. However, delay in receiving the initial responses precluded the second consultation round from being carried out.

A DIAGNOSTIC METHOD TO DETERMINE AQUIFER SUSCEPTIBILITY

1. INTRODUCTION

An earlier ODA TDR project (R5544) into the overexploitation of aquifers (Adams and MacDonald 1995) developed the concept of *Aquifer Susceptibility* to side-effects of groundwater exploitation. A diagnostic method was developed which integrated various standard hydrogeological parameters to provide an initial screening of the potential for adverse effects resulting from groundwater exploitation.

The approach used three indices H, I and S, to represent the *susceptibility* of an aquifer to groundwater decline, saline intrusion and subsidence respectively. Thus the susceptibility of an aquifer was deemed to depend on each index as shown:

Susceptibility	Water level decline	Saline Intrusion	Subsidence
Slight	$H < 5$	$I < 3$	$S < 2$
Significant	$5 < H < 8$	$3 < I < 5$	$2 < S < 3$
Severe	$8 < H$	$5 < I$	$3 < S$

Each index having been calculated by summing a number of weights; the value of each weight depending on certain factors.

The methodology proposed that the overall *susceptibility* should be expressed as susceptibility to groundwater level decline; this evaluation then being qualified, if appropriate, by reference to the susceptibility to saline intrusion and/or land subsidence. Some factors in the determination of susceptibility to saline intrusion and land subsidence relate to the rate at which these effects occur rather than the severity or magnitude of the occurrence. It was recommeded therefore that these factors (e.g. permeability) should be used to provide qualification to the main statement of *susceptibility* e.g.:

> *The aquifer system under consideration is susceptible to groundwater level decline with no likelihood of saline intrusion but severe susceptibility to land subsidence, the full effects of which may not be seen for a significant period of time.*

In the previous study (Adams and MacDonald op. cit.), it was recognised that this diagnostic methodology required further development; it was seen as a first step in development of an approach having potential for wide application as a planning and management tool. The next step in this development was to provide specific weights and ranges for the individual parameters used in assessing aquifer *susceptibility*. This report describes the ODA TDR project (R6533) designed to achieve that next step.

2. THE WORK PROGRAMME

In order to establish a consensus of weights and ranges for the separate hydrogeological parameters involved, it was planned to use an approach based on the Delphi method (Benarie 1988, Aller et al 1985). A number of practising hydrogeologists worldwide would be sent a circular explaining the concept of susceptibility and the parameters thought to be relevant. By means of a questionnaire, they would be asked to comment on the methodology, comment on the proposed weights and ranges for the separate parameters and note any parameters that they felt has been omitted. The results were then to be analysed and an initial consensus evaluated. Respondents to the first circular would then be advised of the resulting initial consensus and asked

Contents

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B Adams, A M MacDonald and T R Shearer

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None

Keyworth, Nottingham, British Geological Survey, 1997

[3.1 Comments]

Massimo Civita	I agree for not indurated sediments And for salt ore, gypsum and soluble rocks?
Robin Herbert	I would have used (S/T) units as indicator consolidation factor ° 1/Cv see attachment
Harriet Nash	Can an aquifer be susceptible to subsidence? Since the subsidence is at the surface, it is the ground that is susceptible. Seems to me that subsidence should be treated separately, or different terminology used.
Alain Dassargues	Do not forget that compressibility is variable with the preconsolidation stress, the effective stress. So that it depends on our main variable : water pressure or piezometric levels!
Jaroslav Vrba	
Antonio Bosch	
Lucila Candela	
Nathalie Doerfliger	= subsidence due to GW withdrawal = changing of fluid pressure in the reservoir due to exploitation in this case
Javier Temino Vela	Compressibility evaluated according to the value of "the coefficient of compressibility" of the aquitard
Doug Kelly	
Ann Williams	I have no experience of these values
Revision	

3.2 Combined Aquitard Thickness - S2

Suggested Weighting **m**	>25 10 - 25 <10	3 2 1
Massimo Civita		
Robin Herbert	Tick	
Harriet Nash		
Alain Dassargues	>30 20 - 30 10 - 20 0 - 10	4 3 2 1
Jaroslav Vrba		
Antonio Bosch		
Lucila Candela		
Nathalie Doerfliger	OK	
Javier Temino Vela	>25 10 - 25 <10	3 2 1
Doug Kelly		
Ann Williams	1-10	1
Revised Weighting	>25 10 - 25 <10	3 2 1

[3.2 Comments]

Massimo Civita	OK
Robin Herbert	Perhaps all one needs to say is that it is an UNSA. If it is an UNSA then it will consolidate as all UNSAs have clay layers. However, could be a minute amount, might have been pre-consolidated. If flat the subsidence can occur evenly over a wide area and may not be important. As it is a geo-hazard approach and not an engineering geology map, don't need to consider pre-consolidation.
Harriet Nash	
Alain Dassargues	It depends more on the accessibility of these aquitards for the Dp propagation through them.
Jaroslav Vrba	
Antonio Bosch	
Lucila Candela	
Nathalie Doerfliger	
Javier Temino Vela	
Doug Kelly	
Ann Williams	0.1m of "compressible" aquitard would have same index as say 100m of "medium" aquitard.
Revision	

3.3 Numbers of Layers - S3

Suggested Weighting	11 - 100 3 2 - 10 2 1 1
Massimo Civita	
Robin Herbert	
Harriet Nash	
Alain Dassargues	> 10 3 2 - 10 2 1 1
Jaroslav Vrba	
Antonio Bosch	
Lucila Candela	
Nathalie Doerfliger	OK
Javier Temino Vela	11 - 100 3 10 - 2 2 1 1
Doug Kelly	
Ann Williams	
Revised Weighting	> 10 3 2 - 10 2 1 1

[3.3 Comments]

Massimo Civita	See comments in 1.2
Robin Herbert	
Harriet Nash	
Alain Dassargues	
Jaroslav Vrba	
Antonio Bosch	
Lucila Candela	
Nathalie Doerfliger	
Javier Temino Vela	I suggest that you consider the possibility of calculating this parameter by a relationship equal to that proposed in part H2, but adapted to aquitards. $\frac{\text{No. layers of aquitards}}{\text{Total no. layers}} \times \frac{\text{Total thickness aquitards}}{\text{Total thickness}}$
Doug Kelly	
Ann Williams	
Revision	Do not agree with Temino's suggestion. Delayed drainage will impact more quickly the greater the number of layers - one thick layer will not drain as quickly as several layers with same total thickness.

3.4 Aquitard Permeability - S4

Suggested Weighting **m/day**	>10 10 - 10^{-3} <10^{-3}	3 2 1
Massimo Civita	>10^{-1} 10^{-1} - 10^{-3} <10^{-3}	3 2 1
Robin Herbert		
Harriet Nash		
Alain Dassargues	>1 1 - 10^{-3} <10^{-3}	3 2 1
Jaroslav Vrba		
Antonio Bosch		
Lucila Candela	>1 1 - 10^{-3} <10^{-3}	3 2 1
Nathalie Doerfliger	Tick	
Javier Temino Vela	>1 1 - 10^{-3} <10^{-3}	3 2 1
Doug Kelly		
Ann Williams		
Revised Weighting	>1 1 - 10^{-3} <10^{-3}	3 2 1

[3.4 Comments]

Massimo Civita	An aquitard which hydraulic conductivity is >10 m/d is a true aquitard?
Robin Herbert	
Harriet Nash	
Alain Dassargues	
Jaroslav Vrba	
Antonio Bosch	>10 m/d = aquitard? The upper value seems high to me to be included in the range of aquitards Have you ythought of including in the susceptibility the special case of collapses as an associated risk of exploitation, and a variation of subsidence? It could be interesting and complementary to your work. Possibly you will have to ?? it to the ?? of karstic aquifers.
Lucila Candela	
Nathalie Doerfliger	Susceptibility to subsidence is generally specific to basin aquifers. But overexploitation in Karst areas such as in ?? may provoke some collapsing ?? How can we take into account this process? Did you test for the influence of each factor on the others and also the sensitivity of variation of each weight, to determine the limit of each resulting susceptibility degree?
Javier Temino Vela	
Doug Kelly	
Ann Williams	10 m/d is very high for an aquitard
Revision	