THE IMPLICATIONS OF GRAVEL EXTRACTION ON GROUNDWATER CONDITIONS

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ABSTRACT : The mining of gravel for construction is a major industry in the United Kingdon. A large proportion of the gravel extracted is from alluvium in river valleys, where groundwater abstraction for water supply purposes is important and farming is extensive. Gravel operations affect the groundwater flow patterns on a short term basis when dry working is carried out and on a long term basis when poor permeability back-filling is used.
The paper outlines the principles of the effects of gravel operations causing derogation of wells, pollution and water loggind of farming land. A digital model is used to illustrate the degree of permanent effects under gravel back-filling in a valley.

RESUME : L'exploitation de gravier pour la construction constitue une industrie importante en Royaune-Uni. Une grande partie du gravier provient d'alluvions de vallées fluviales où existe une extraction intensive d'eaux souterraines pour la consommation humaine et l'usage agricole. L'extraction du gravier affecte la distribution de l'écoulement souterrain pendant peu de temps lorsque l'opération se réalise à sec et pendant longtemps lorsqu'on utilise un colmatage de faible perméabilité.
Ce travail présente les effets de l'extraction de graviers qui entraîne l'abandon des puits, la pollution et l'inondation de la terre du chantier. On utilise un modèle digital pour illustrer la permanence des effets sous un colmatage de gravier dans une vallée.

RESUMEN : La explotación de grava para la construcción constituye una importante industria en el Reino Unido. Gran parte de la grava procede de aluviones de valles fluviales en los que existe una extracción extensiva de aguas subterráneas para consumo agrícola y humano. La extracción de la grava afecta a la distribución del flujo subterráneo durante poco tiempo cuando la operación se realiza en seco, y durante largo tiempo cuando se usa un relleno de baja permeabilidad.
Este trabajo presenta los efectos de la extracción de gravas que traen consigo el abandono de pozos, la polución y el encharcamiento de la tierra de labor. Se utiliza un modelo digital para ilustrar la permanencia de los efectos bajo un relleno de grava en un valle.

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Introduction

With the reorganisation of the water industry in the United Kingdom increased attention is being paid to many of the minor aquifers in the country among which may be listed the widespread river-valley gravels. Parallel with the developing groundwater interest in these deposits is the continued extraction of gravel and sand for the construction industry and the growing environmental problems of pollution and land reclamation related to extraction sites. In certain areas, therefore, there can exist a conflict of interests in a gravel deposit: the gravel extractor may be interested in the deposits as a material, and the water-supply engineer in the water-bearing potential of the deposit. As the availability of construction materials decreases and the development of groundwater resources and environmental and pollution controls increases, a much clearer understanding of the implications of gravel extraction for water supply will be required, so that, where possible, compatible development for both industries can proceed.

The possible impact of gravel abstraction on the groundwater situation is outlined and discussed here. The gravels that are most likely to provide a dual resource potential are those in the valley floor, as these will probably be water-bearing. Higher-level terrace gravels may not contain water. If it is present, however, the situation is analogous to the valley-floor gravels. A digital model representation is used to illustrate some of the long-term effects of gravel extraction operation.

Short-Term Impact

The impact of gravel abstraction upon groundwater should be considered both in the short term and in the long term. The short-term problems can be listed under five broad categories: groundwater abstraction from workings, which may result in derogation of neighbouring water supplies (Figure 1); phenol pollution, which may enter the aquifer from site plant; bacterial pollution of surface water in working pits, which may be transferred into the aquifer; siltatio of secondary permeability aquifers and induced polluted recharge, drawn into the workings from neighbouring rivers, which may be introduced into the aquifer saline water can be a problem in estuary areas.

Groundwater abstraction during gravel extraction can sometimes reach large prop ortions; derogation is inevitable in the overall context, although locally it will depend upon the detailed groundwater flow distribution. Irrespective of the local derogation situation, however, a disposal of good-quality water to polluted rivers or canals frequently occurs - which is obviously poor management of resources. Planning authorities therefore increasingly include in

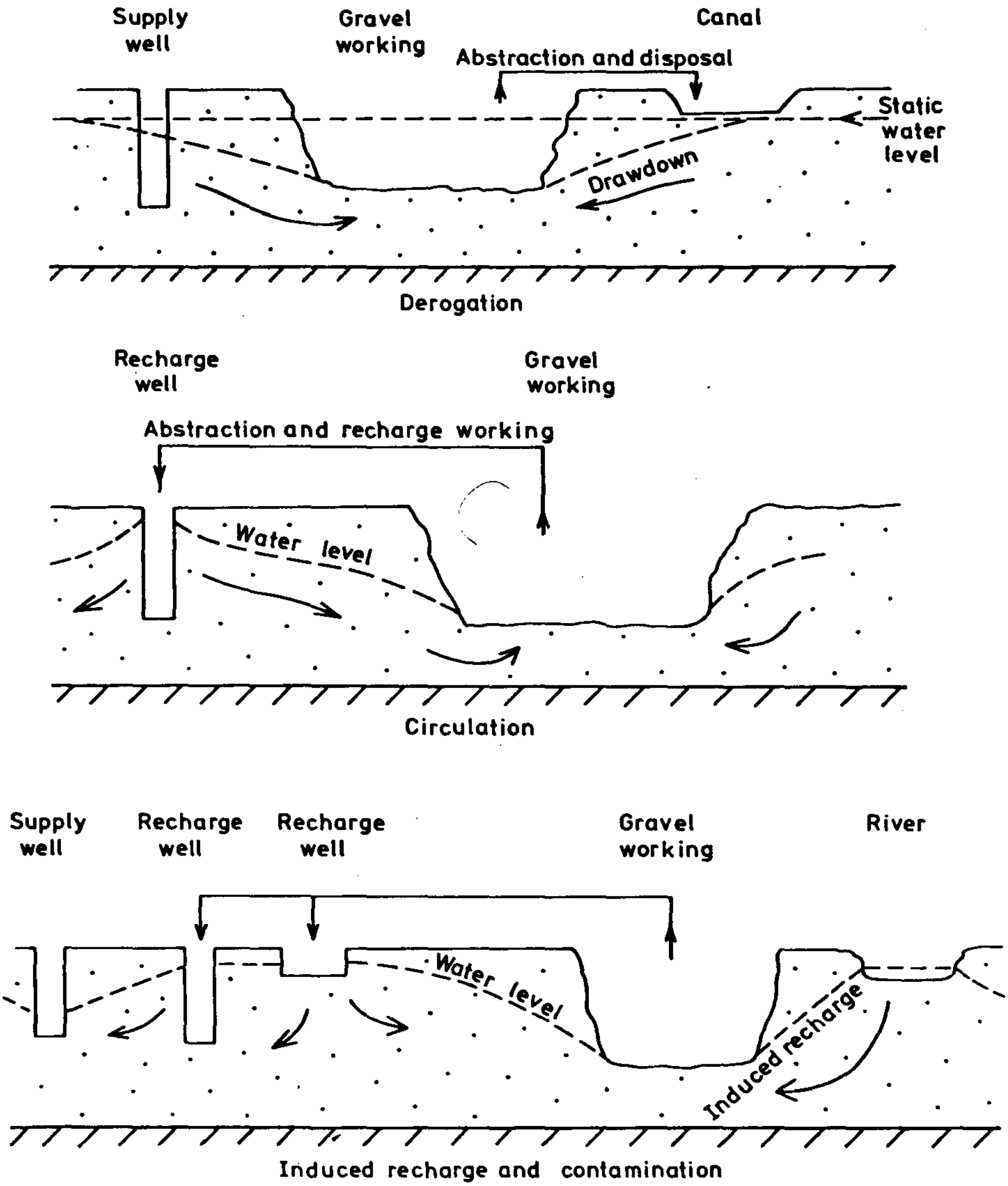


Figure 1. Possible derogation and contamination of water supplies

their planning requirements for extraction sites,clauses that demand that abstracted groundwater should be returned to the aquifer. Such requirements undoubtedly impose constraints on the gravel extractor, but in groundwater terms they may not be totally realistic; for, although the return to the aquifer of groundwater by artificial recharge techniques is in concept simple, in reality it can be difficult.

Artificial recharge can be carried out by spreading and basin techniques or recharge wells. Several factors can, however, mitigate against effective recharge:

(i) the volume of water to be returned to the aquifer is likely to require a large prepared recharge area where spreading is proposed ;

(ii) recharge wells can prove expensive ;

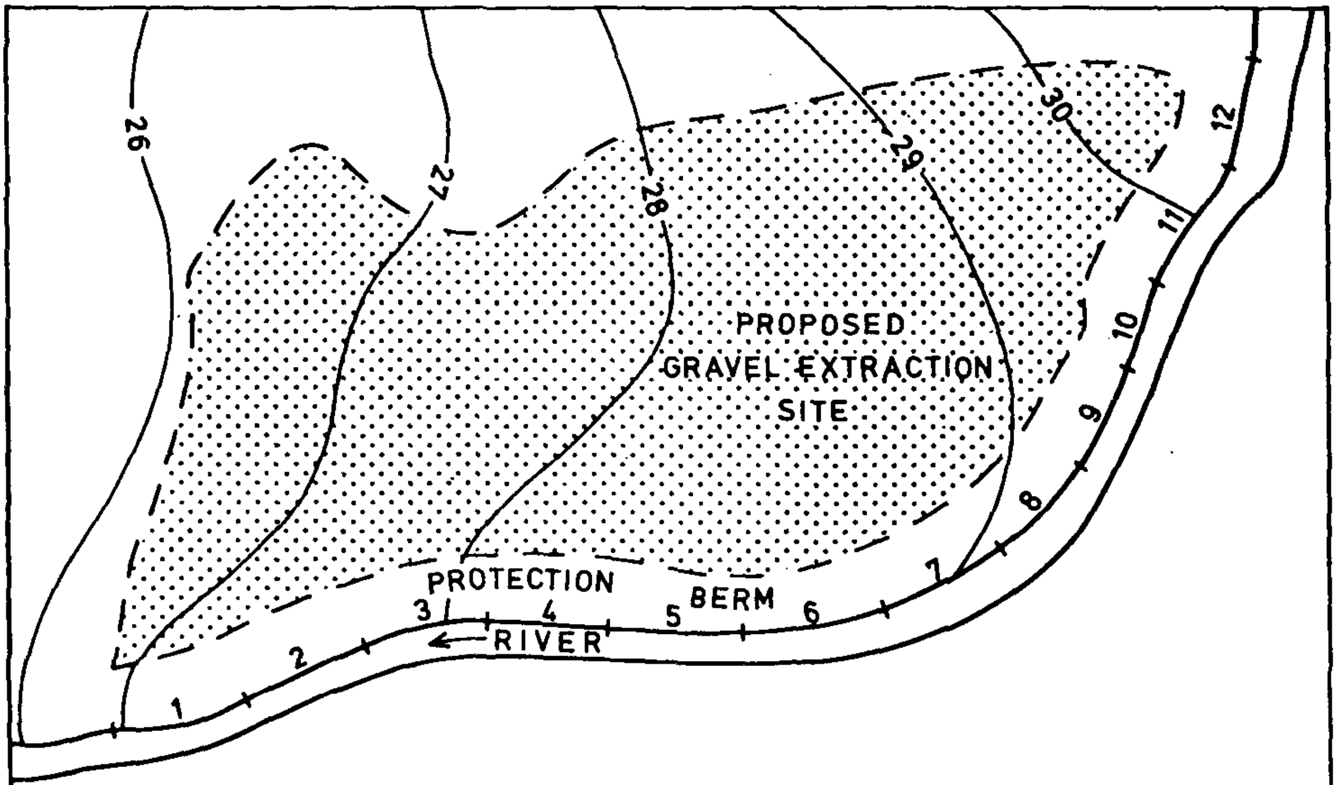
(iii) as a cone of depression will exist around the extraction site, a recharge mound must be located at an adequate distance to avoid circulation (Figure 1) - this is particularly critical with well input, as steep groundwater gradients may be created ;

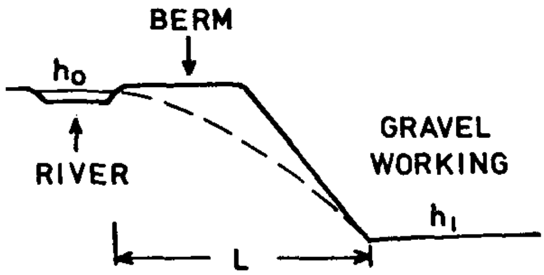
(iv) groundwater velocities may be high under recharge gradients, so that polluted water can be rapidly introduced into the aquifer (Figure 1);

and (v) gravel operators may well produce aerated and turbid water, which, if introduced directly into the aquifer, can reduce effective permeability, and algal growth in spreading areas can reduce effective permeability.

If gravel extractors wish to work valley gravels, they may therefore eventually be faced with only two alternatives: either to operate under water, or to artificially recharge, despite the inherent difficulties. As can be seen from the calculations given on Figure 2 the possible flow into a proposed gravel working can be large so that the ensuing derogation and artificial recharge can be considerable. Undoubtedly, most of the recharge problems can be overcome with experience, but the extractor must expect to embark upon a reasonably comprehensive hydrogeological study of the site and adjacent areas before extraction is commenced, and to formulate a definite recharge policy that will minimize the wastage of groundwater resources. It seems probable that a certain amount of field experimentation may be required by the extractor for a decision on the most cheap and efficient methods.

The short-term pollution problems vary in degree. Phenol pollution can be minimized by careful plant operation. If large spillages occur, these can usually be skimmed off and pumped to waste. A certain amount of low-level bacterial pollution of open water surfaces in gravel pits is inevitable, and its significance with respect to neighbouring supply wells will depend upon groundwater travel times within the aquifer. A residence of two weeks will usually reduce most bacterial content to acceptable levels. Where artificial recharge is being practised, the possibility of the direct introduction of phenols and bacteria to the aquifer will require attention, and the location of the recharge site will be important.





Possible Inflow Calculation

$$Q = Km \frac{h_o^2 - h_i^2}{2L} \ (m^3/day)$$

1	95	7	324
2	735	8	344
3	780	9	392
4	340	10	435
5	595	11	642
6	621	12	189
			5492
Groundwater flow			950
			6442 m^3/day = Final abstraction requirement for dry work.

K = coeff. of permeability

m = section width

Figure 2. Gravel working in flow calculation

The problems of polluted recharge from neighbouring rivers, etc., into gravel workings, as a function of abstraction, may be difficult to assess before operations. It can prove the most severe of the pollution hazards, particularly where artificial recharge is to be adopted, in that high levels of inorganic and organic pollutants may be introduced into the aquifer. The chief difficulties lie in the assessment of the permeability of the adjacent river bed, the distribution of this permeability and the possible inflow values. Although pumping tests at selected well-sites may provide information about induced recharge through yield-drawdown analysis, hydrochemical data, tracers, etc., the drawdown effects of a large pit operation will undoubtedly prove more extreme with time. Any indications from the investigation stage that induced polluted water can occur must, therefore, jeopardize the development of a deposit as a material resource, or at least restrict extraction to a safe distance from the polluted source.

Potential pollution hazards should also be considered where old backfilled gravel workings are present near a new site. In certain cases, untreated refuse may have been used as backfill material. Dewatering of the new site can disturb the groundwater and hydrochemical situation in the backfilled area and induce polluted water into the groundwater system.

Where gravel extraction occurs in deposits overlying fissured aquifers siltation can pose problems and effectively reduce permeability. It is unlikely that siltation will be extensive under normal groundwater velocities; however, if active pumping wells are close to an extraction site then high velocities may occur and siltation may become a serious problem. Some assessment of the likely transport velocities and the particle sizes involved may be obtained from Figure 3.

Long-Term Impact

The long-term impact of gravel extraction upon groundwater concerns the reclamation of the extraction site after operations have terminated, or progressive reclamation during operations. Two basic situations can occur: either the pit is left open, or it is backfilled. The long-term decision in this respect is the responsibility of the local planning authorities. Preference varies throughout the country, and is dependent largely upon the requirements of farming, sporting amenities, waste disposal, etc. The impact on the groundwater resources is largely overlooked.

Where the planning permission imposes no backfill requirements on the extractor, the position is relatively straightforward. The presence of a large open body of water in a groundwater system can, however, pose problems. The hydraulic continuity between the open water area and the aquifer is the most important factor. If good continuity exists, then it may be asked whether pollutants such as coliform bacteria, which will undoubtedly be present in amenity areas, are likely to degrade before they enter a supply well. In general, continuity is reduced by the growth of algae along the sides and base of the pit, and a fairly impermeable flow-barrier situation may develop under steady-state conditions. This impermeability, although it reduces pollution of the aquifer, may, however, seriously affect the local groundwater flow distribution (see below) (Figure 4).

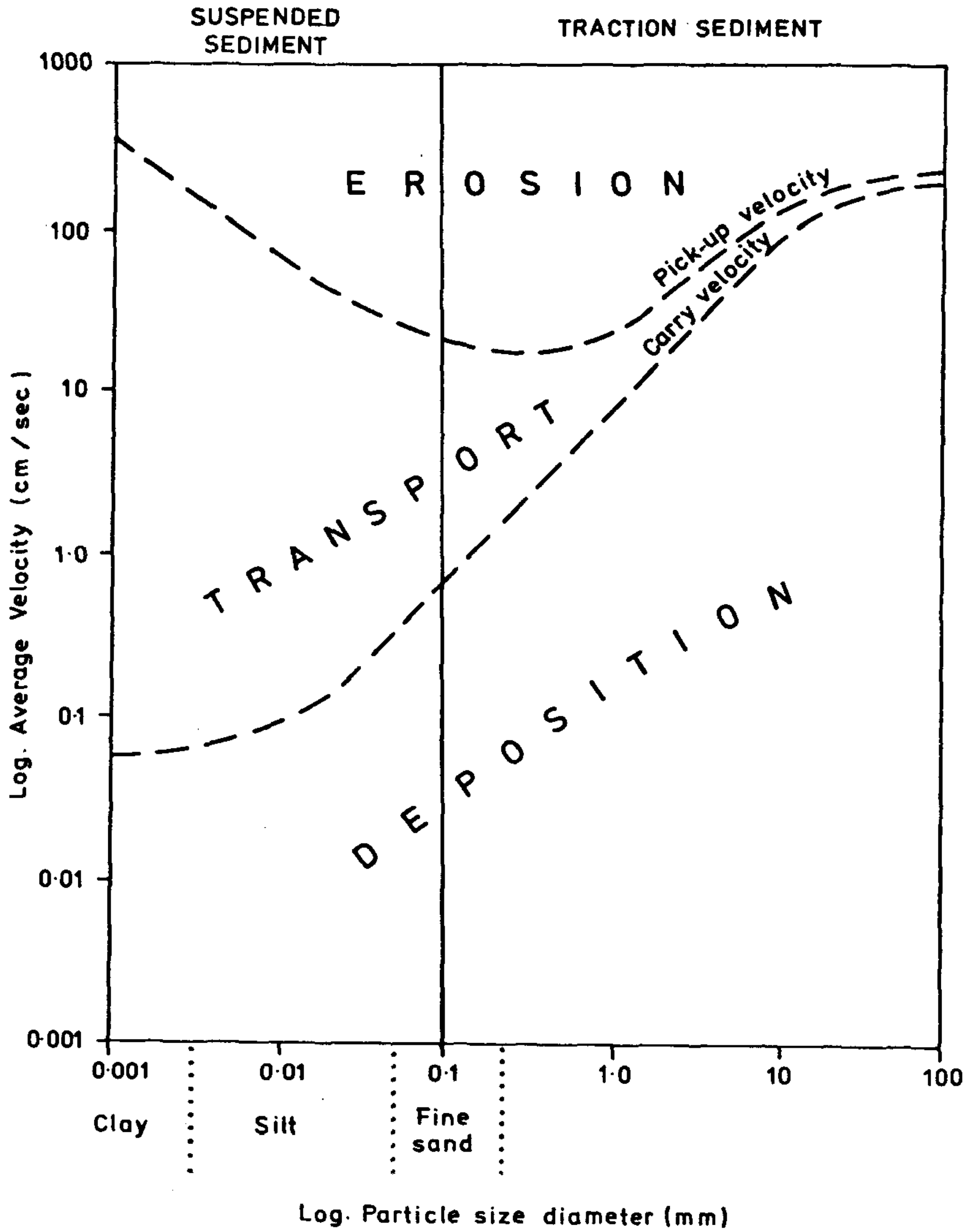


Figure 3. Particle transport

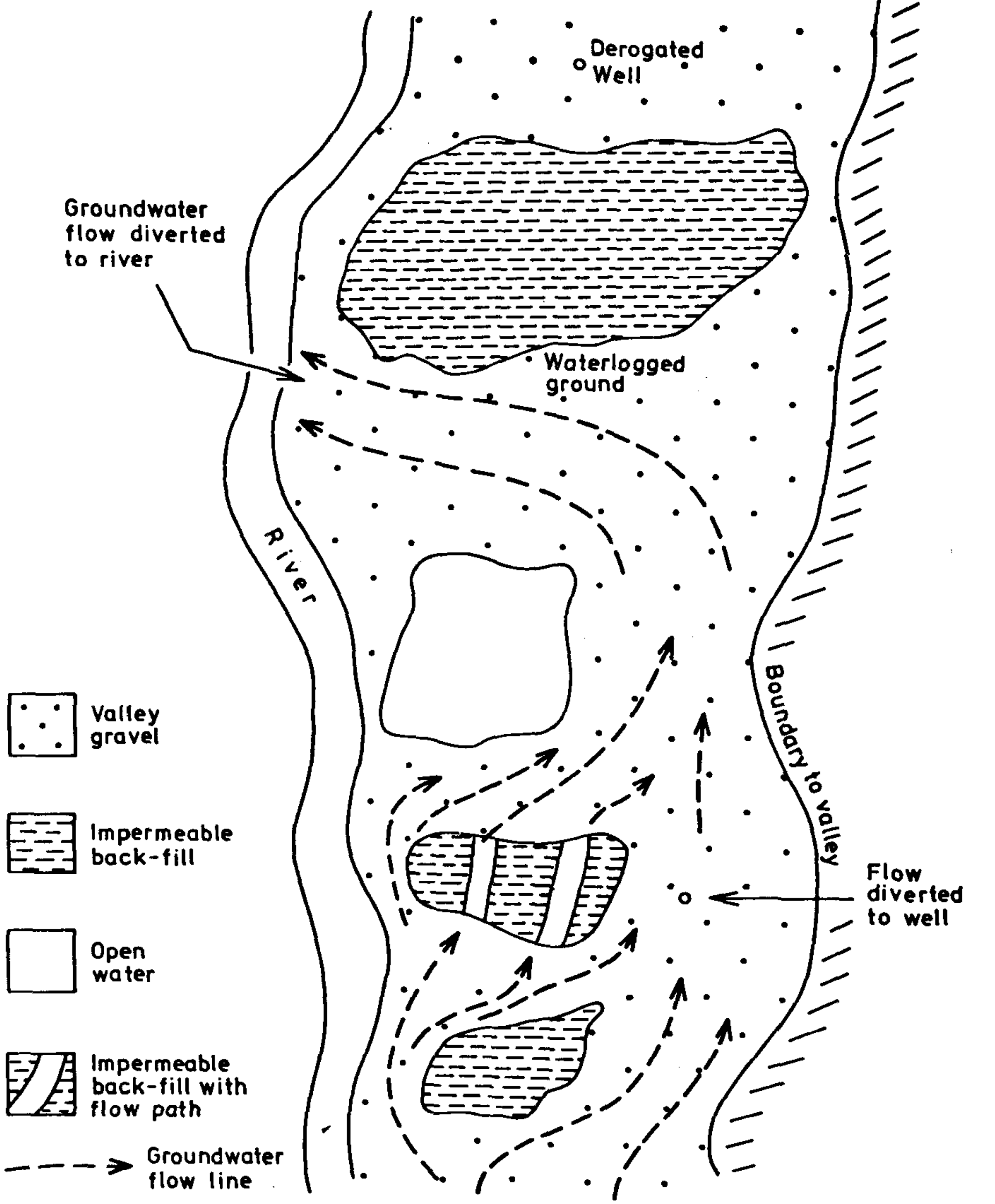


Figure 4. Local flow of ground water

The extent of the impermeable zone will be important: if it is too large, groundwater flow will be significantly curtailed and long-term derogation of downstream supplies may result. With an extensive impermeable backfill zone, groundwater can either be forced to the surface - which results in water logged land - or move into adjacent water courses, where possibly it may be lost into a polluted system (Figure 4). Where an impermeable zone of only minor extent is created, the flow distribution can, in fact, be disturbed to the advantage of the water abstractor in that flow may be diverted towards a well. Whatever the extent of an impermeable backfill, the possible effects on the groundwater flow pattern of its introduction should be analysed prior to implementation.

In general, from a water-supply viewpoint, the exclusive use of impermeable backfill should be avoided. Where possible, an attempt should be made to maintain an acceptable groundwater flow through backfilled sections. This could be achieved either by retaining permeable flow paths of in-situ gravel through the site, or by planned backfill operations with permeable waste materials used to create flow paths through impermeable sections. Problems obviously arise for the extractor, in that, in the first case, the extractable amount of gravel is reduced, and, in the second, backfill operations may become more expensive owing to the batching of materials. Whichever technique is adopted, the problems of grading and filtration between materials will have to be examined to avoid siltation of the flow paths. Despite the difficulties, however, the introduction of flow paths in backfill sections may well become a requirement of future planning permissions for extraction sites (Figure 4).

To illustrate the groundwater disturbance problems involved in gravel workings a digital model example from northern England may be used. The model has been prepared to study further gravel extraction and back-fill operations in an already disturbed valley. The valley is typical with gravel thickness ranging up to 12 m and is underlain by marls with thin limestones.

Where the planning authorities require that the gravel extractor should back-fill a site, stipulations vary. Frequently, reclamation for agricultural purposes is envisaged, and the chief requirements are related to suitable top soils. Backfill is stipulated down to a certain level, but below the 'agricultural zone' fill materials are often left to the discretion of the gravel extractor. Backfill materials that can be used are basically fine-grained tailings and overburden from the gravel pit area, industrial and domestic waste.

As the gravel extractor will be working the highest-grade gravels, the removal of these materials will, in itself, radically disturb groundwater conditions. The degree of permanent disturbance, however, will depend upon the nature of the backfill material. Undoubtedly, the tailings will be incorporated in the backfill, reducing the permeability of the ground. Additional fine-grained waste material such as pulverized fly ash will frequently be used, and will effectively create flow-barrier conditions within the aquifer (Figure 4).

A classical hydrogeological study was carried out in the valley and simulation of the aquifer was obtained using the equation adopted by Walton (1970) which describes the time - variant drawdown throughout an aquifer when the vertical components of flow are considered sufficiently small to be neglected.

$$\frac{\partial}{\partial x}\left(T_x \frac{\partial s}{\partial x}\right) + \frac{\partial}{\partial y}\left(T_y \frac{\partial s}{\partial y}\right) = S \frac{\partial s}{\partial t} + Q \qquad \text{(i)}$$

where Tx and Ty are the transmissivities in the x and y directions, s is the drawdown, S is the specific yield of the aquifer in this case and Q is the quantity of water entering the aquifer per unit area per unit time. For a practical solution of the equation throughout the aquifer system time and space dimensions were divided into discrete intervals (Pinder and Bredehoeft, 1968) and for the finite difference approximation a backward difference approach was adopted (Rushton, 1973) in which

$$T_x \frac{\partial^2 s_{n+1}}{\partial x^2} + T_y \frac{\partial^2 s_{n+1}}{\partial y^2} = S \frac{s_{n+1} - s_n}{t} + Q_{n+\frac{1}{2}} \qquad \text{(ii)}$$

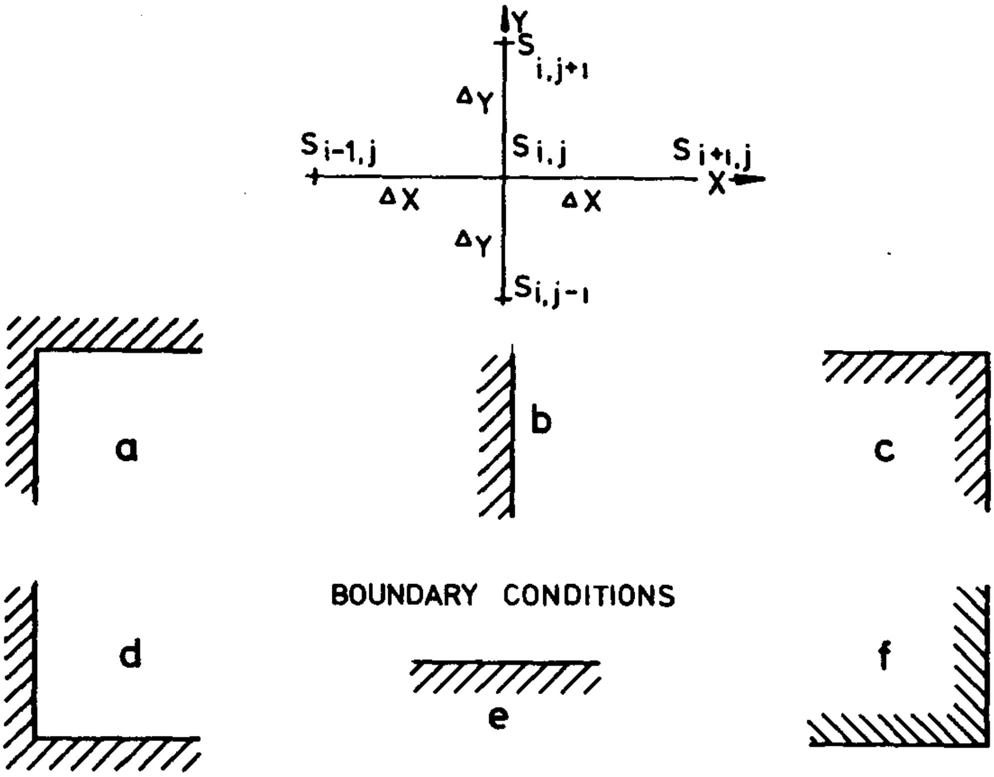
With this approximation the space derivative is centred at a time (n+1) Δt and the time derivatives at time (n+½) Δt. For computational purposes the aquifer is divided into a grid with a nodal distribution (Si, j) as shown on Figure 5 and equation (ii) is given as

$$T_{x,i,j} \left[\frac{s_{i+1,j} - 2s_{i,j} + s_{i-1,j}}{\Delta x^2}\right]_{n+1} + T_{y,i,j} \left[\frac{s_{i,j+1} - 2s_{i,j} + s_{i,j-1}}{\Delta x^2}\right]_{n+1}$$

$$= S \frac{s_{i,j,n+1} - s_{i,j,n}}{\Delta t} + Q_{i,j,n+\frac{1}{2}} \qquad \text{(iii)}$$

The boundary condition of a 'fixed head' is applied directly by retaining the appropriate head at the specified value. For an impermeable boundary the condition of 'no flow' crossing the boundary s/y = 0 is applied through a fictitious node i,j+1 by setting $S_{i,j+1} = S_{i,j-1}$. The finite difference approximations lead to a large number of simultaneous equations which were solved using iterative over-relaxation techniques (Rushton, 1974).

To construct the model, the area was subdivided on a grid as shown in Figure 6 with grid intersections representing data input nodes equally spaced at 0.5 km. intervals. The area of influence for each node is a square 0.5 x 0.5 km. based on the node as a centre point. Using the basic data obtained from field studies namely transmissivity, specific yield, recharge and groundwater level, values were selected for each adjacent nodal pair. In the non-boundary affected nodal areas these values were balanced with surrounding nodal areas using the groundwater flow equation discussed above. Where



TRANSMISSIVITY FACTOR

	X	Y	-X	-Y
a	0·5	0·0	0·0	0·5
b	1·0	0·5	0·0	0·5
c	1·0	1·0	0·5	0·5
d	0·5	0·5	0·0	0·0
e	0·5	1·0	0·5	0·0
f	1·0	0·5	0·5	1·0

SPECIFIC YIELD FACTOR

a	b	c	d	e	f
0·25	0·50	0·75	0·25	0·50	0·75

Figure 5. Boundary modification factors

SIAMOS-78. Granada (España)

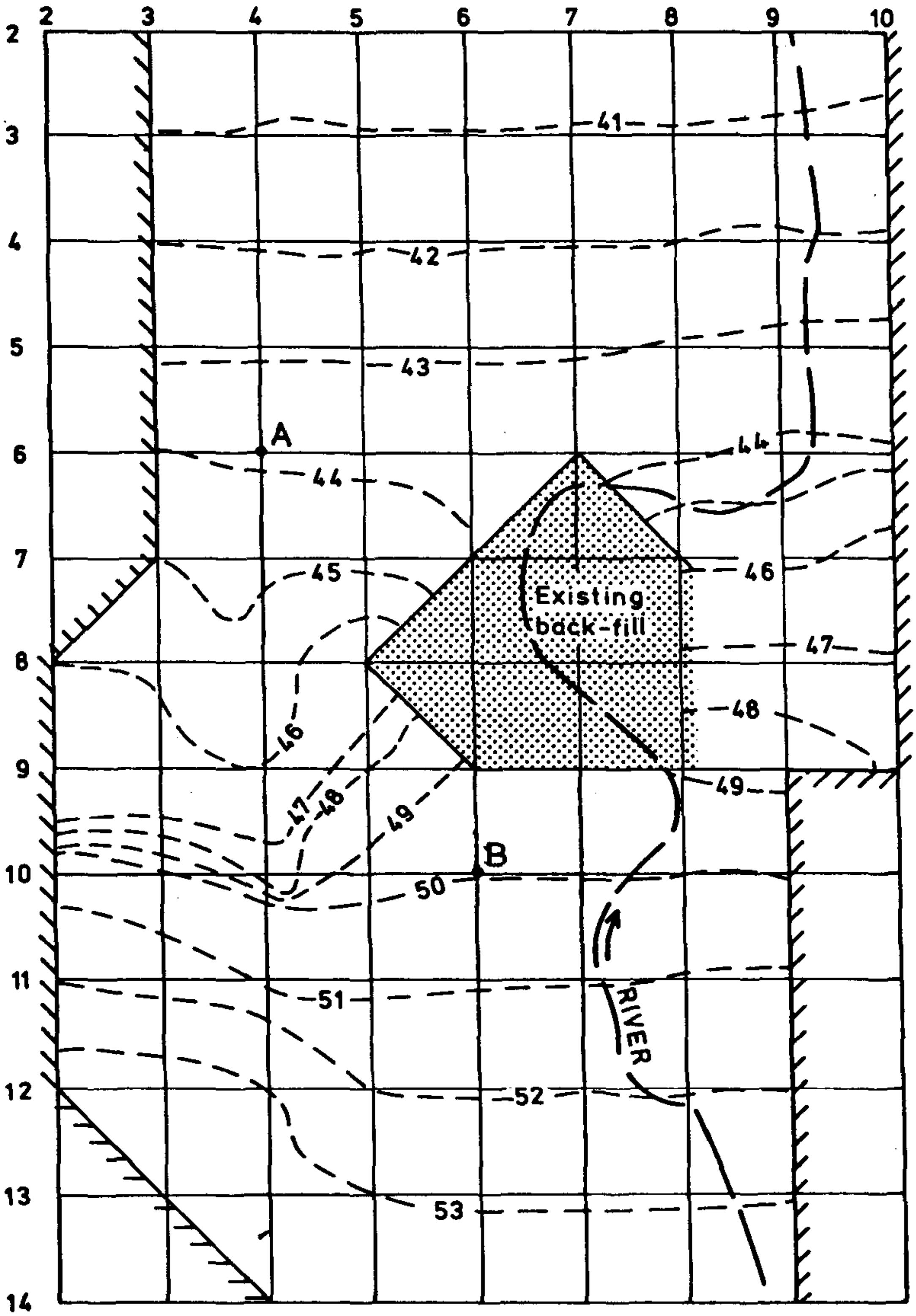


Figure 6. Geometry of model area

boundaries are present different approaches were used. The eastern boundary of the aquifer was determined as a boundary of 'no flow' and along the western boundary a minor recharge was applied due to the presence of some lateral leakage from thin limestones. Otherwise the boundary was treated as a 'no flow' boundary. The northern and southern boundaries were varied seasonally in relation to well hydrograph data.

In attempting to obtain a simulation considerable difficulty was experienced in matching well hydrographs in the area west of the existing back-filled area. In this narrow section and in such a thin aquifer it was found that the simulation was most sensitive to transmissivity; specific yield though also important, proved less sensitive in the model as shown in Figure 7. Eventually a close simulation was obtained and the piezometic surface shown in Figure 6 was portrayed.

The object of the study was to evaluate the effects of proposed further abstraction of gravel west of the existing back-filled area with subsequent impermeable back-filling. Two major problems were envisaged, firstly the derogation effects on well complex A downstream of the proposed workings and secondly the possibility of water-logging of ground in the vicinity of B. In the model the long-term back-fill was increased in three stages as shown on Figure 6 and the water level responses obtained at the two investigation points varied as shown on Figure 8.

From Figure 8 it will be seen that although the water level at A drops slightly the ground permeability is adequate to transmit the diverted groundwater and derogation in theory is not serious. However, the levels at B are seen to rise extremely close to the ground surface in stage 2 and it is anticipated would cause local unacceptable water-logging. Under stage 3 conditions, surface discharge would occur and in fact the water level at A would no doubt drop considerably as the model has only allowed for groundwater flow and discounted surface flow.

The model has therefore demonstrated that although minor extensions to the gravel operations may be contemplated (i.e. stage 1) no further operations should be allowed under the proposed impermeable fill reclamation programme. It is feasible however, that should adequate permeable fill be incorporated in the back-fill that more gravel may be extractable over and above stage 1 without seriously disturbing groundwater conditions.

Conclusions

The potential groundwater development of gravel deposits can, in many situations, be irrevocably reduced by inadequate planning of gravel extraction. It may be argued that in some areas planning authorities should place a complete restriction on gravel extraction to safeguard groundwater flow and long-term water supplies. Elsewhere, provided that adequate hydrogeological data have been obtained and the effects of extraction and backfill methods have been tested, it is reasonable to expect that gravel extraction can progress in harmony with water supply.

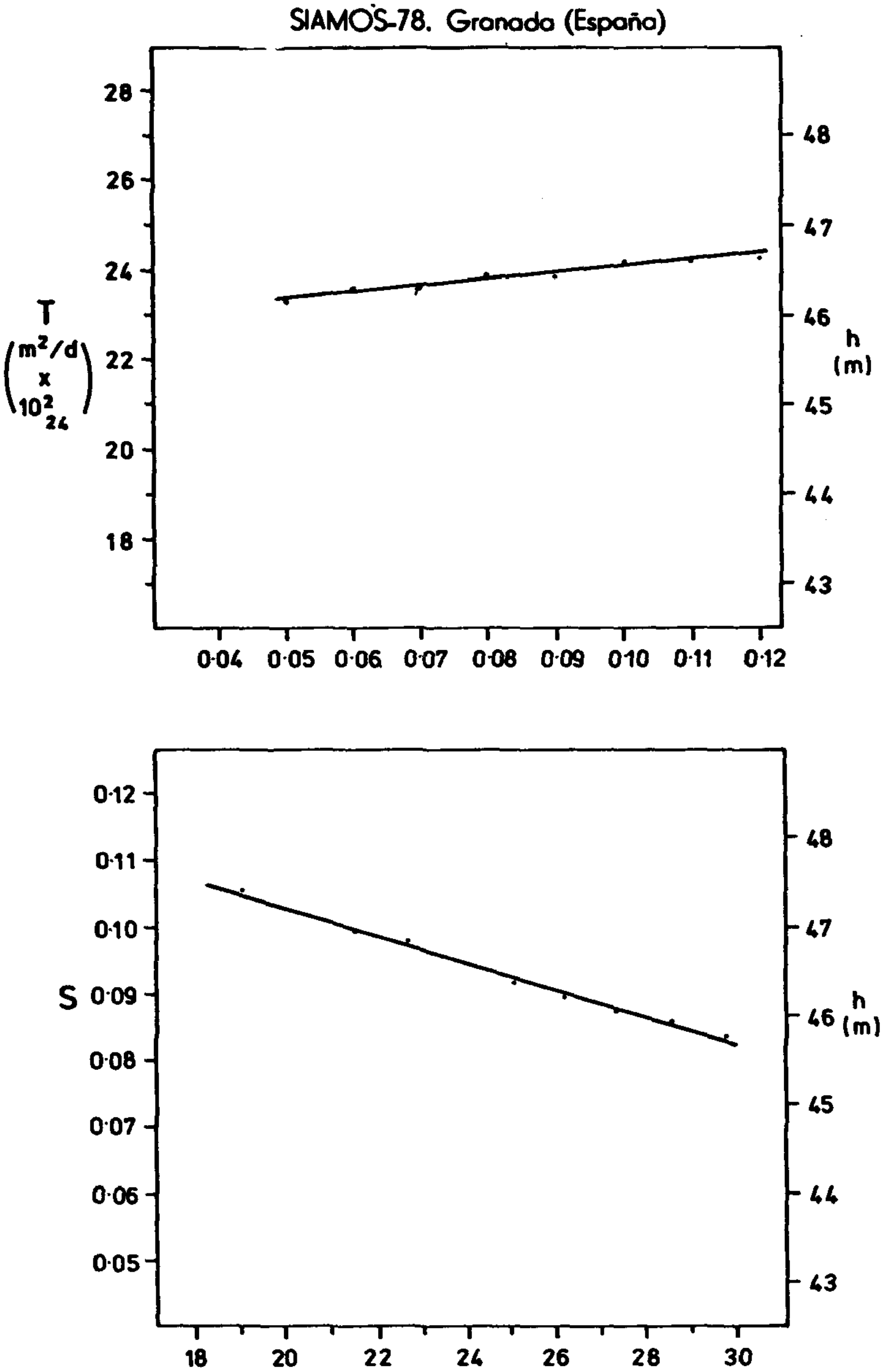


Figure 7. Model sensitivity to T and S

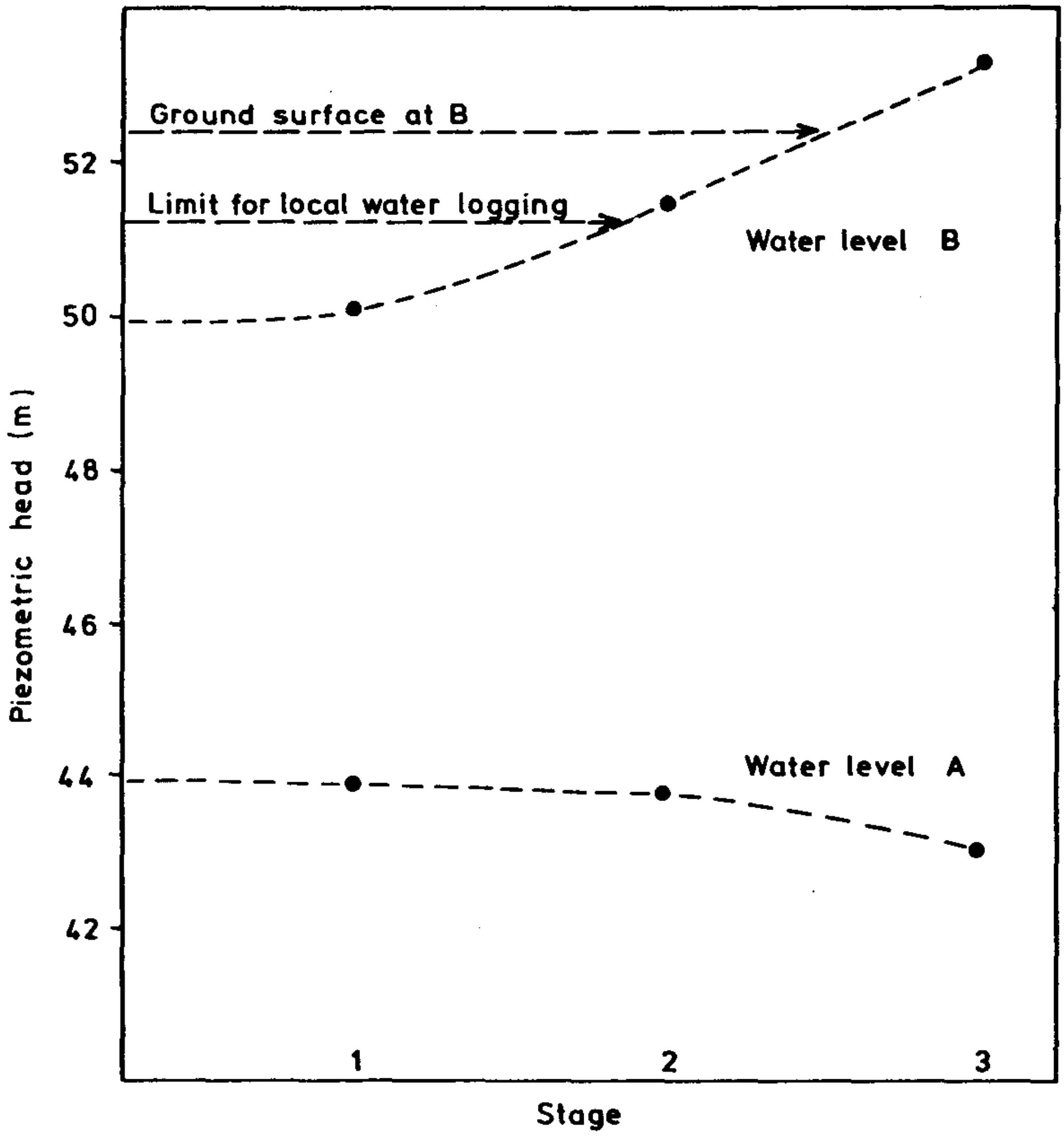


Figure 8. Effect of proposed back-fill operation

The overall responsibility for compatible development ultimately rests with the planning and water authorities. Because of the potential danger to water supply, there is a possibility that planning requirements for extraction sites could become unrealistic; there is a need for direction on both the short- and long-term techniques that can be adopted to solve the dual development of gravel deposits. Undoubtedly, much of the technical onus will fall on the gravel operators, with the increased costs which they imply. As the availability of construction materials continually decreases and the environmental and water-supply constraints multiply, increased costs are inevitable.

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