Quantitative analysis of saline intrusion problems of the Northern coastal plain of Java

DR C.R. REEVE

Institute of Hydrology

Sir Alexander Gibb and Partners
Earley House
427 London Road
READING
RG6 1B2

23 December 1985

Attention: *Mr B Brent*

Dear Brian

JAVA SALINE INTRUSION

Following our recent discussions we have pleasure in enclosing a draft review of saline intrusion modelling with a short bibliography, which we hope will meet your needs for further discussions with AAAT.

Please add any comments that you might have.

May I take this opportunity of wishing you a Happy Christmas.

Yours sincerely

R B Bradford

RBB/JH

RB

Contents

Summary

1. The continuing development of the groundwater resources along the north coast of Java ~~to~~ is leading to saline ~~instruction~~ intrusion problems that will eventually restrict the utilisation of these resources. Groundwater management models which take into account saline intrusion will be required for planning and investment decisions.

2. Management decisions can be made on the ~~ais~~ basis of monitoring the aquifer system. This is expensive and, by itself, will only provide qualitative predictions. However, by linking observations with mathematical models the behaviour of the system and its response to abstraction can be more effectively understood thereby enabling more ~~quantative~~ quantitative predictions.

3. The development of predictive models to represent the complex hydrogeological conditions of northern Java as well as the saline intrusion effects will require expert skills and the use of large computers.

4. Recognising the potential problem and the need for expert advice, Agency for the Assessment and Application of Technology (AAAT) held initial discussions with Sir Alexander Gibb and Partners (SAGP) during the recent visit by British consultants to ~~Thailand~~ Indonesia. As a result of these discussions Institute of Hydrology (IH) have prepared on behalf of SAGP a brief review of saline instrusion and the various factors which need to be taken into account. This is accompanied by a short list of the major published articles on saline intrusion.

5. Any quantative and predictive model of saline intrusion must consider three important aspects : the scale and geometry of the problem under consideration, the characteristics of the aquifer system, and the processes associated with the interface between fresh and salt water. These factors largely determine the type of model required and the extent to which simplifying assumption can be applied.

6. The complexity of the aquifer system along the north coast of Java suggests that a phased modelling procedure would be appropriate. This would begin with a simple model and progress in stages to more complex representations of the system by including such factors as ~~hydrometric~~ hydrodynamic dispersion and well abstraction. The ultimate objective for predictive purposes would be three-dimensional, finite element, time-varying,

local/regional model incorporating hydrodynamic dispersion.

7. To be successful the modelling procedure must involve the training of model users familiar with the local hydrogeology. These staff would then be in a position to properly advise managers and to update the model with new information. In addition, development of a model serves to focus the collection of data.

8. IH is actively engaged in programmes of research into groundwater models of saline intrusion and, through their consultancy services, have experience overseas in the application of such models. Their specialist staff are able to assist in the preparation of an initial conceptual model of the system, developing the appropriate mathematical description and translating this into computer programs which can be combined with actual data to represent to real system. They are also able to offer appropriate training in the theory and application of saline intrusion models.

Introduction

The Agency for the Assessment and Application of Technology (AAAT) advises the Indonesian government on the introduction of advanced technology and liaises with external consultants who can offer expert advice. During a recent visit by SAGP, as part of a visit by British consultants to Indonesia, the problem of saline intrusion along the north coast of Java was discussed with AAAT. Whilst the problem of saline intrusion appears to be most serious in the region round Jakarta, it affects the whole of the northern coast. It is due to the over-extraction of groundwater for potable, industrial and irrigation use, however it is possible that ~~that~~ some of the water quality problems are a result of salinisation of groundwater due to return irrigation water.

IH are actively engaged in research into saline intrusion. They were approached by SAGP to discuss the possible application of computer models to the Java situation. A mathematical model of the saline intrusion would allow both a quantitative understanding of the present situation and future prediction. Predictions could be made ofthe consequences of continuing the present abstraction regime and also to assist management decisions aimed at alleviating or even reversing the saline intrusion. An additional advantage of such a saline intrusion model would be that it could be used as a management model for the groundwater resources of the area.

In this review the application of quantitative analysis to saline intrusion is discussed. Some of the various alternative models available are presented with discussion of their applicability to northern Java. In addition, we have indicated the type of data that is required to decidewhich mathematical model would be most appropriate and also that required to calibrate the model. We also suggest briefly the manner in which the modelling might be carried out and a way of transferring the advanced technology that would be utilised for the model.

2. The hydrogeology of Northern Java

Northern Java consists of two distinct geological regions: in the west and central region the coastal plain consists of thick Quaternary (Pleistocene to Holocene) alluvial sediments whereas in the east there are

Tertiary Limestone formations.

The Jakarta artesian basin and the northern coastal plain of central Java consist of thick Quaternary alluvial sequences which are locally of high groundwater potential. These aquifers generally consist of thin gravel or sand layers intercalated between clay layers. In these coastal plains saline or brackish water-bearing layers are often found above as well as below the confined freshwater aquifers.

In the Tertiary Limestone formations of the eastern coastal plain of northern Java groundwater is unevenly distributed. These limestone formations have solution fissures and caverns and the groundwater potential in these areas depends mainly on the intensity of solution channelling.

3. The occurrence of Saline Intrusion

There usually exists a hydraulic gradient towards the sea in coastal aquifers. Due to the existence of salt water in the aquifer formation under the sea bed there is a contact zone, known as the saline interface, between the lighter fresh water which is flowing towards the sea and the heavier salt water. Typically there exists a body of sea water, often in the form of a wedge underneath the fresh water. The contact zone between the fresh and salt water takes the form of a transition zone across which the density of the mixed water varies from that of fresh water to that of salt water.

Under undisturbed conditions a state of equilibrium exists with a stationary saline interface and a fresh water flow to the sea above it. If fresh water is pumped from the coastal aquifer in excess of natural replenishment the saline interface will advance inland to a new equilibrium position. As well as causing an advance inland of the saline interface, pumping results in an increase in the width of the transition zone. If the pumping rate is sufficiently high the consequence of this change of position and thickness will be contamination of the abstraction wells.

There exists a relationship between the rate of fresh water discharge to the sea and the extent of saline intrusion. Sea water encroachment is a management problem since the fresh water discharge is the difference between the rate of natural and artificial replenishment and pumping.

4. Quantitative analysis of saline intrusion

The contamination of fresh water, by salt water, whether it be natural or man induced, significantly reduces the potability of the fresh water. Thus a quantitative understanding of the patterns of movement and mixing of fresh and saline water is required. Increasingly complex mathematical models of the fresh-salt water interaction have been developed over the last 100 years. These models can be used to investigate the physical processes which affect saline intrusion and also to study different management regimes which can be used to conserve and protect the fresh water resource.

An exact mathematical statement of the saline intrusion problem is extremely complex. No analytical solution exists for this problem and, until recently, no computers were sufficiently large to solve the problem numerically. Assumptions have been made about the flow which occurs in coastal aquifers to simplify the mathematical statement of the problem. These assumptions lead to mathematical models that can be solved numerically, and, in their simplest form, analytically. These assumptions can be catagorised into three inter-related groups: the physics of the mixing process, those about the aquifer characteristics and the geometry and scale of the aquifer/problem under study.

4.1 The physics of the mixing process

The saline interface consists of a transition zone across which the fluid density varies from that of salt water to that of fresh water. Under certain cicumstances it is reasonable to assume that the width of the transition zone is very small so that an abrupt interface approximation can be introduced. This would be justified when the interface thickness is small relative to the thickness of the aquifer; or when there is a rapid groundwater flow so that the solute transport is dominated by advective rather than dispersive processes. When the abrupt interface approximation is made the fresh and salt water are treated as two miscible (non-mixing) fluids. Nonetheless, the mathematical statement of the miscible flow problem is still complex since one of the boundary conditions is the location of the saline interface which is non-stationary.

Other assumptions are often introduced to simplify the problem still further. The simplest of these is the Ghyben-Herzberg approximation

(Badon-Ghyben, 1888 and Herzberg, 1901), which assumes that there is static equilibrium and horizontal flow in the fresh water zone and that the salt water is stationary. Under these circumstances the depth to the saline interface is 40 times the distance below sea level that the water table is above sea level. However, the Ghyben-Herzberg approximation is not valid close to the coast since the fresh water flow is not horizontal and, since the saline interface must be at sea level at the coast, there is no outlet for fresh water, a physically unreasonable assumption. Where there is a lack of data, the Ghyben-Herzberg approximation, despite its drawbacks, is often the best model of saline intrusion that can be used.

Other more complex analytical abrupt interface models have been derived by Muskart (1937) and Hubbert (1940). More recently numerical techniques have been used to solve the immiscible flow problem. A good description of these is given in Bear (1979) Chapter 9.

In the context of the northern coastal plain of Java it is unlikely that an abrupt interface approximation will be reasonable as the aquifer is multi-layered and within each layer the interface thickness is likely to be a significant proportion of the aquifer thickness. Groundwater flow in these aquifers is slow due to their generally low transmissivity. Thus solute transport will be dominated by dispersive rather than advective processes and an abrupt interface approximation would not be justified. In order to confirm these statements lithological and conductivity profiles are required from fully screened boreholes and information is required on groundwater flow velocities.

A further reason why the miscible flow assumption may not be reasonable is because groundwater abstraction is of great importance within the aquifers under study. The effect of well abstraction is to cause a movement inland and thickening of the saline interface and thus in order to accurately represent the effect of well abstraction the thickness of the saline interface must be modelled. Work has been carried out within the Institute of Hydrology to determine the effect on both the position and thickness of the saline interface of well abstraction (Reeve and Wikramaratna, in preparation).

In order to model the thickness of the saline interface the effects of hydrodynamic dispersion must be introduced, where the groundwater is treated as a miscible fluid which varies in density from salt water to fresh water across the saline interface. Hydrodynamic dispersion is the irreversible process by which a solute being transported by the groundwater flow occupies a volume greater than would be expected according to the average flow.

Two processes contribute to hydrodynamic dispersion: mechanical dispersion and molecular diffusion. Mechanical dispersion is caused by variations from the average groundwater flow velocity and molecular diffusion occurs due to the nonhomogeneous distribution of solute molecules. Despite much research on the subject over the last 30 years the phenomenon of hydrodynamic dispersion is not fully understood and a complete mathematical statement of the physical processes involved has not been derived. Detailed summaries of this research work can be found in Bear (1969, Chapter 4 and 1972, Chapter 10) and Fried (1975).

It is generally agreed that both mechanical dispersion and molecular diffusion are a function of the concentration gradient of the solute. In the case of molecular diffusion the proportionality factor is the molecular diffusion for the aquifer under study. This is often taken as being a proportion (usually between 1/3 and 2/3) of the actual coefficient of molecular diffusion for the solute under consideration. For mechanical dispersion Bear and Backmat (1967) expressed this coefficient as a function of aquifer ~~matric~~ matrix geometry, flow velocity and molecular diffusion. The influence of aquifer matrix geometry on the coefficient of mechanical dispersion is known as the dispersivity of the porous medium. The definition of this property is extremely complex but if the aquifer can be considered as isotropic it can be simplified to a function of two constants, the longitudinal and transverse dispersivity of the aquifer. A good description of the mathematical representation of hydrodynamic dispersion is given by Bear (1979) Chapter 7.

The complete representation of hydrodynamic dispersion described above is mathematically complex and requires parameter values which are extremely difficult to measure in the field. Due to these problems simplified techniques for representing hydrodynamic dispersion have been utilised. These include taking the coefficient of hydrodynamic dispersion as constant or as a linear function of the flow velocity. Mathematical models have been developed at the Insitute of Hydrology using the Bear and Bachmat representation of hydrodynamic dispersion (Wikramaratna and Wood, 1981).

These have been used to investigate the effect of representing the dispersion process in different ways and to study the effect that varying the values for the aquifer dispersivities have on both the position and thickness of the saline interface.

A miscible flow model is required to represent the saline intrusion which occurs on the northern costal plain of Java. Initially, this model should use a simplified representation of the coefficient of hydrodynamic dispersion. To obtain a good simulation the complex Bear and Bachmet representation may be required. If this is the case tracer tests will be required to obtain estimates of aquifer dispersivities.

The saline intrusion models described above assume that there is no chemical interaction between the groundwater and solid matrix of the aquifer. The effect of chemical interaction is to either advance or retard the transport of the solute relative to the mean velocity of groundwater flow. When the solute being transported is salt and the aquifer matrix consists mainly of sands and gravels this is a physically reasonable assumption. However, if there is a significant proportion of clay within the aquifer there may be some chemical interaction with the solute. These chemical processes can be represented by isotherms which model the transfer of solute between the solid and fluid phases. These isotherms are usually derived from laboratory experiments.

4.2 Aquifer characteristics

Saline intrusion models have been applied mainly to aquifers whose characteristics can be assumed to be homogeneous and isotropic. In reality aquifers such as these rarely if ever exist. Thus a second important consideration when deriving a saline intrusion model is the spatial and directional variation of aquifer properties. If an aquifer consists of a number of distinct layers separated by aquicludes there will be a multiple saline interface. The exact position of the interface in each layer will depend on the aquifer properties of that layer and, similarly, the relative positions of the interface in the different layers will depend on their relative properties.

Inhomogeneties in aquifer properties can be represented in saline intrusion models. However, there are difficulties in representing anisotopic permeability if the full representation of the hydrodynamic dispersion tensor is used. As stated previously the dispersivity of the porous medium can only be simplified for an isotopic aquifer.

Much research is being carried out in an attempt to derive a representations of the coefficient of hydrodynamic dispersion in anisotropic aquifers. The Institute of Hydrology has recently embarked on a research project to investigate the effect of aquifer inhomegeneties on saline intrusion. This project has involved the development of a specialist instrument to look at 'in-situ' pore water salinity in shallow heterogeneous aquifers. The collected data will be used to calibrate numerical models of saline intrusion.

A model of the northern coastal aquifers of Java will need to take account of the multi-layered nature of these aquifers. In order to decide to exact form of the model detailed lithological profiles are required to subdivide the aquifer into its different layers. Field and laboratory determination of aquifer properties are required to calibrate the model.

4.3 Geometry and Scale

The modelling of saline intrusion as a miscible flow problem is clearly a three-dimensional phenomenon. Since 3-D solute transport models are extremely demanding on both computer memory and time, approximations are often made which allow the problem to be reduced to the modelling of a 2-D vertical section perpendicular to the coast. This can be achieved by making use of symmetries which occur in the area to be modelled or alternatively by using a "representative" 2-D vertical section. In complex aquifers the assumptions that allow the use of these quasi 3-D models are usually not applicable and thus fully 3-D solute transport models are required.

If an immiscible flow model is used the problem can be represented by a 2-D areal model, which are cheaper computationally but suffer from the major drawback that vertical variations in aquifer properties cannot be represented.

The multilayered nature of the aquifers of the northern coastal plain of Java suggest that a quasi or fully 3-D representation will be required to model the saline intrusion.

Saline intrusion can be modelled as either a steady-state or time-varying phenomenon. Steady-state models are used when the system is in equilibrium. When changes to the system are occurring, whether they be natural or man induced, a time-varying model should be utilised. This is the case in Java where aquifers are affected by abstraction. Such a model will allow history matching against collected data and also extrapolation into the future to predict the consequences of different management regimes. Initially, a steady-state saline intrusion model could be used to investigate the natural equilibrium position and thickness of the saline interface.

The scale of the problem being studied should also be considered when developing a model. If flow and solute transport in a large region are to be modelled a much coarser numerical grid is required than if saline intrusion is to be simulated in a localised area, such as at a single abstraction well. The scale of the area to be modelled also affects the data requirements: a localised model will require extremely detailed data at one site whereas a regional model requires data from many sites over a large area.

As well as considering the physical size of the system to be modelled the different numerical techniques which exist to solve the derived mathematical equations must be selected. In general, finite element techniques are used for solute transport modelling because of the greater flexibility they offer in grid definition to allow accurate representation of complex aquifer property variations and external boundaries. Efficient equation solving techniques must be used to minimise the use of computer time and storage whilst ensuring a convergent solution. Research has been carried out to derive special numerical techniques for use in solute transport problems such as that undertaken at Institute of Hydrology (Wikramaratna and Wood, 1983).

Once a computationally efficient model of saline intrusion has been developed a calibration process must be carried out. This requires both spatial and temporal information on groundwater flow and solute transport. Once the model has been calibrated it can be used to predict the consequences of future management options.

5. The modelling procedure

Because of the complex nature of saline intrusion modelling it is usual to start the modelling process with simple model, which, in most cases, would be a numerical, sharp-interface model. Once this model had been calibrated the effects of hydrodynamic dispersion can be introduced perhaps initially employing a constant coefficient of hydrodynamic dispersal. Eventually a more complex representation such as that derived by Bear and Bachmat may be required.

In terms of aquifer properties the initial model would usually assume homogeneity. Later models could introduce inhomogeneity and anisotropy if this was required to obtain a better simulation. In the context of Java the coastal aquifer could be represented by a two-layered system consisting of a semi-confined aquifer overlain by a pheatic aquifer. This would be a better initial approximation of aquifer properties than the assumption of homogeneity.

Whilst a steady-state saline intrusion model could be used to study the equilibrium position of the saline interface, an investigation of the effect of well abstraction would require a time-varying model.

6. Technology Transfer

Saline intrusion modelling is normally carried out on mainframe computers due to the large computational requirements. This work should be based in the UK because of the large range of computers available. As part of the UK-based modelling activities, staff from Indonesia could be trained in both the theory and practical use of saline intrusion models with the additional benefit that these staff could attend one or more of the many groundwater flow and solute transport modelling courses that take place every year in Europe. Once the derivation and calibration of the saline intrusion model has been completed it could be transferred to computers in Indonesia. These models could then be used as part of the ongoing management of the groundwater resources on the northern coastal plain of Java.

References

Listed below in alphabetical order are papers and books referred to in the text together with some other important papers on saline intrusion. A more complete saline intrusion reference list can be obtained from the author.

Bear, J., 1969. Hydrodynamic dispersion in flow through porous media (ed R.J.M. De Wiest,) Chapt 4 pp 109-200, Academic Press, New York.

Bear, J., 1972. Dynamics of Fluids in Porous Media, American Elsevier, New York, 764 pp.

Bear, J., 1979. Hydraulics of Groundwater, McGraw-Hill, 567 pp.

Bear, J. and Y. Bachmat, 1967. A generalised theory on hydrodynamic dispersion in porous media. IASH Symposium on Artificial Recharge and Management of Aquifers, Haifa, Israel, IASH Publ. No.72, pp 7-16.

Fried, J.J., 1975. Groundwater Pollution, Elsevier, Amsterdam, 930pp.

Baden-Ghyben, W., 1888. Nota in Verbord met de Veorgenomen Putboring Nabj, Amsterdam (Notes on the probable results of well drilling near Amsterdam).Tiljdschr. Kon. Inst. Ing. The Hague, pp8-22.

Herzberg, A. 1901. Die wasserversorgung einiger Nordssebaden (The water supply on parts of the North Sea coast in Germany) Z. Gasbeievchi Wasserversorg. 44 815-819, 824-844.

Hubbert, M.K. 1940. The theory of groundwater motion. J. Geol. 48(8) 785-944.

Lloyd, J.W., R.H. Pim, M.D. Watkins and A. Suwara, 1985. The problems of groundwater assessment in the volcanic-sedimentary environment of Central Java. QJ. Eng. Geol. 18. pp47-61.

Muskat, M. 1937. The Flow of Homogeneous Fluids through Porous Media. McGraw-Hill, New York. 763 pp.

Reeve, C.E. and R.S. Wikramaratna, ~~1986~~ in preparation. A model to simulate the effects of abstraction on a saline interface in a porous median. (Being prepared for submission to Groundwater.)

Reilly, T.E. and A.S. Goodman, 1985. Quantitative analysis of saltwater-freshwater relationships in Groundwater systems - a historical perspective. Journal of Hydrology, 80. 125-160.

United Nations, 1980. Groundwater in the Pacific Area.

USGS, 1964. Sea water in Coastal Aquifers. Water Supply Paper 1613-C.

Wikramaratna, R.S. and W.L. Wood, 1981. On the coupled equations of the groundwater quality problem: In Numerical Methods for Coupled Problems. ed. E.Hinton, P. Bettess and R.W. Lewis, pp60-75. Pineridge Press.

Wikramaratna, R.S. and W.L. Wood, 1983. Control of spurious oscillation in the saltwater intrusion problem. Int. Journ. for Num. Meth. in Eng. 19. 263-281.