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THE MOVEMENT OF FRESH WATER INJECTED IN SALAQUIFERS

SUMMARY

The storage of fresh water in a significant quantity is not only possible in surface water reservoirs or phreatic aquifers but also in aquifers that are (partially) saline or brackish. When these aquifers are located at greater depths, injection can only be accomplished with wells.

The present study will provide a theoretical basis for predicting the movement of bubbles of fresh water injected in saline aquifers. In the modelling use is made of vortex-theory to simulate the flows of the liquids with different densities. Factors that affect recovery efficiency will be reviewed.

1. INTRODUCTION

When surface water is the sole source for supply of drinking and industrial water, there must be a storage in order to guarantee an uninterrupted supply. Spin-off advantages from storage are that by selective intake plus the decomposition and mixing processes that occur the quality of the water can be further improved. Storage in times of ample river flow of sufficient quality can be provided by open reservoirs or by recharge of groundwater. This paper deals with storage facilities that can be created underground by displacing salt

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water. Before this can be applied in practice on operational scale a number of questions must be answered. Among these are recovery results and the extent to which formation of brackish water is likely to occur. Irregularities in soil structure play an important part in this connection. This is why several Dutch waterworks use field tests to study this phenomenon. Investigation of the parameters governing displacement of one fluid by the other includes resort to calculation methods for simultaneous flows of fluids with different densities.

2. REVIEW OF WORK BY OTHERS

Possibilities for using saline aquifers to store fresh water have been studied extensively both with field tests and laboratory experiments. Josselin de Jong computed the rate of tilting of an interface in a confined aquifer using vortex distributions. The results were verified by a parallel plate model and an electric resistance model [6].

Gardner et al studied static gravity segregation of miscible fluids in linear horizontal models [3]. Esmail and Kimbler did the same in synthetic sandstone models [2]. The results of these experiments were used in a computer-program to calculate recovery efficiencies in hypothetical aquifers. Computed recoveries of fresh water ranging from 25 to 85% are reported. Kimbler [7] described flow studies in artificial sandstone models that have been used to test the above mentioned computational technique for predicting the recovery efficiencies. Moulder [11] reviewed factors that affect recovery of fresh water stored in saline aquifers and compared recovery results of several field tests. Efficiencies ranged from 0 to 50%. Efficiency is defined as the percentage of injected water recovered before a detectable amount of native water was observed. Recoveries obtained experimentally in artificially consolidated models costructed by Kumar and Kimbler ranged from 8.5 to 87.6% [10].

So far all investigations have been for single-well radial systems. Whitehead however extended it to well field [14] and Kimbler et al studied a method to counteract the effects of pre-existing groundwater movement [8].

Most of the above mentioned investigations deal with rather thin aquifer, fully penetrating wells and small density differences thus leading to favourable conditions for high recovery efficiencies. The aim of this paper is to discuss cases of convective currents in rather thick aquifers. Those currents can be significant if density differences and permeabilities are large.

3. VORTEX THEORY

To calculate the transient and simultaneous flows of fresh and salt groundwater only those models can be used that do consider both horizontal and vertical flow components of all fluids. The computerprogram BUBBLE that is developed for this study uses vortex-theory, the principle of which will be described below.

It was first recognised by de Josselin de Jong that density differences create rotations in the flow. This rotation can be modeled with singularity or vortex distributions whose action is such that interfaces are tilted (back) to a horizontal position. The concept of vortex theory is to replace all fluids with different densities by one hypothetical fluid and then to introduce singularities at those places where the densities of the actual fluids change [6]. The vortices generate the effect of varying density. By applying the principle of superposition the resulting flow can be computed. It consists of two parts. One of them is accounting for the effects of the density differences, the other for the flow of the hypothetical fluid.

Vortex distributions were first implemented in computer programs for two-dimensional groundwater flow by Haitjema [4]. Later on he elaborated the velocity components for the flow resulting from vortex rings for use in axial-symmetric models [5]. Stability criteria for vortex computer programs have been derived by Peters [12]. All this is used in the computerprogram BUBBLE. Results and possibilities will be discussed in the next few paragraphs.

4. BUBBLES IN INFINITE MEDIA

Bouyancy effects of spherical foreign fluid substances in infinite aquifers with both a different viscosity and density can be calculated directly by solv-

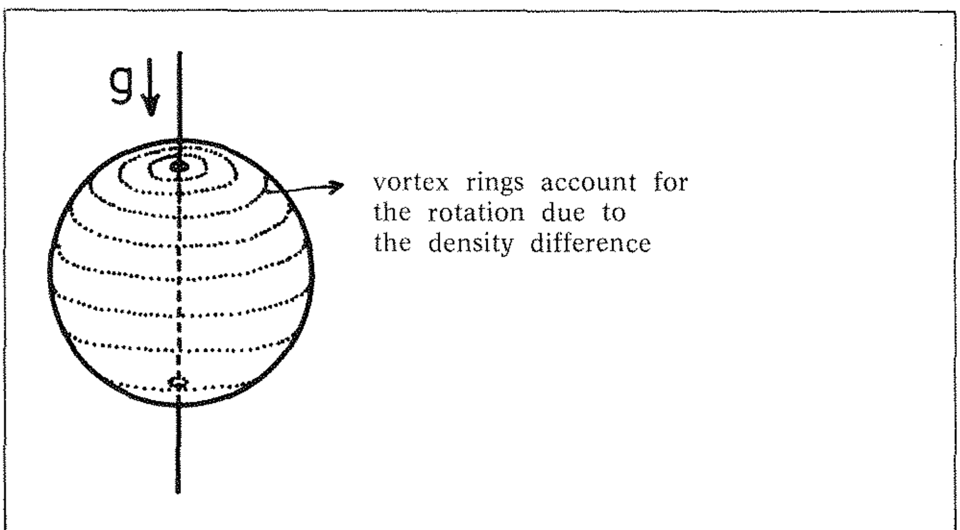
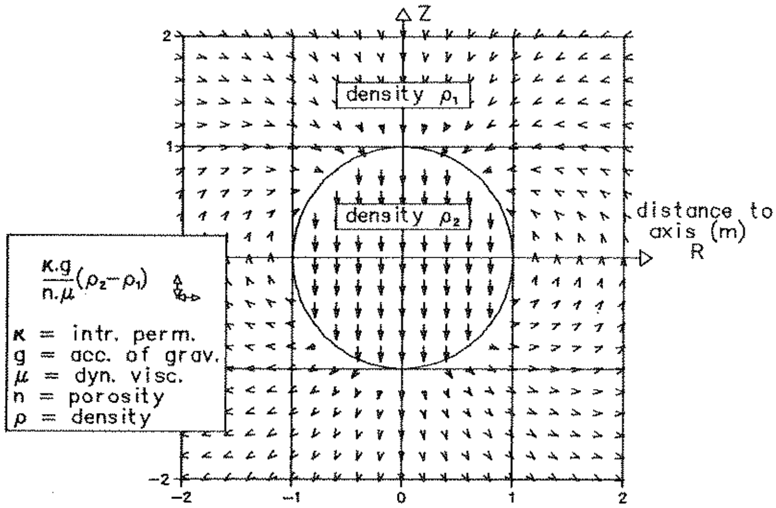


Fig. 1 - A distribution of vortex rings.



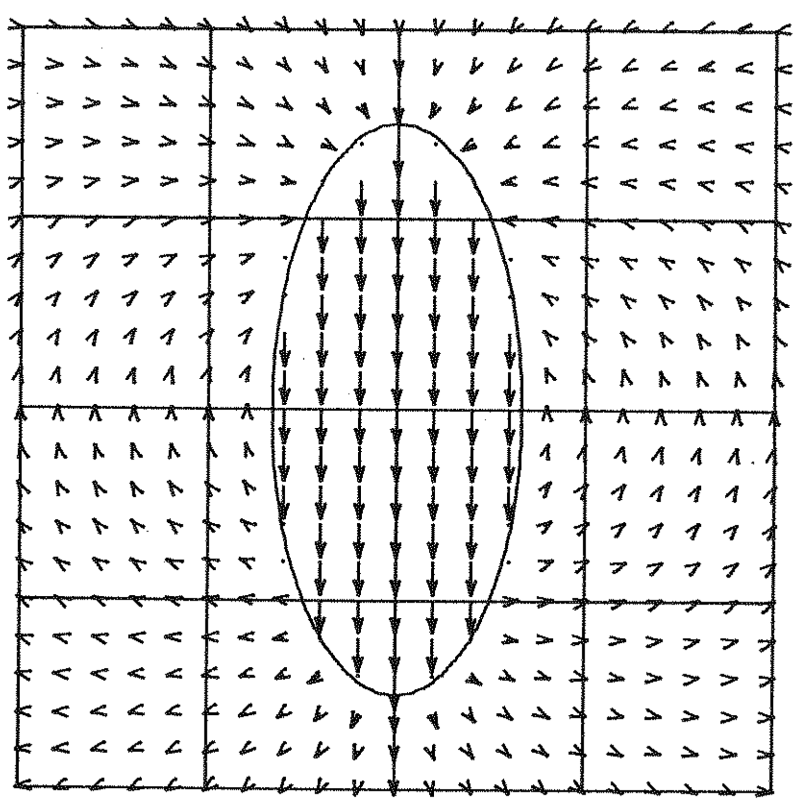


Fig. 2 and 3 – Velocity fields when heavy fluids sink through infinite aquifers. Maximum downward velocity related to velocity of native fluid turns out to be α. Velocities solely depend on shape of bubble, not on dimensions.

ing the Laplace equation [9]. When only the density of foreign and native fluids differ down- or upward velocity of the bubble turns out to equal 2/3 times α. In this connection α is defined as a constant of gravitational segregation (L/T)

$$\alpha = \frac{k}{n} \frac{\Delta\rho}{\rho} = \frac{Kg}{n\mu} \Delta\rho$$

(Used notations are explained at the end of this work).

This result can also be elaborated by introducing vortex rings between the both fluids, see Figure 1.

To check the computerprogram BUBBLE some tests have been carried out. The velocity field that exists when heavy foreign fluid sink through infinite aquifers are presented in Figure 2 and 3.

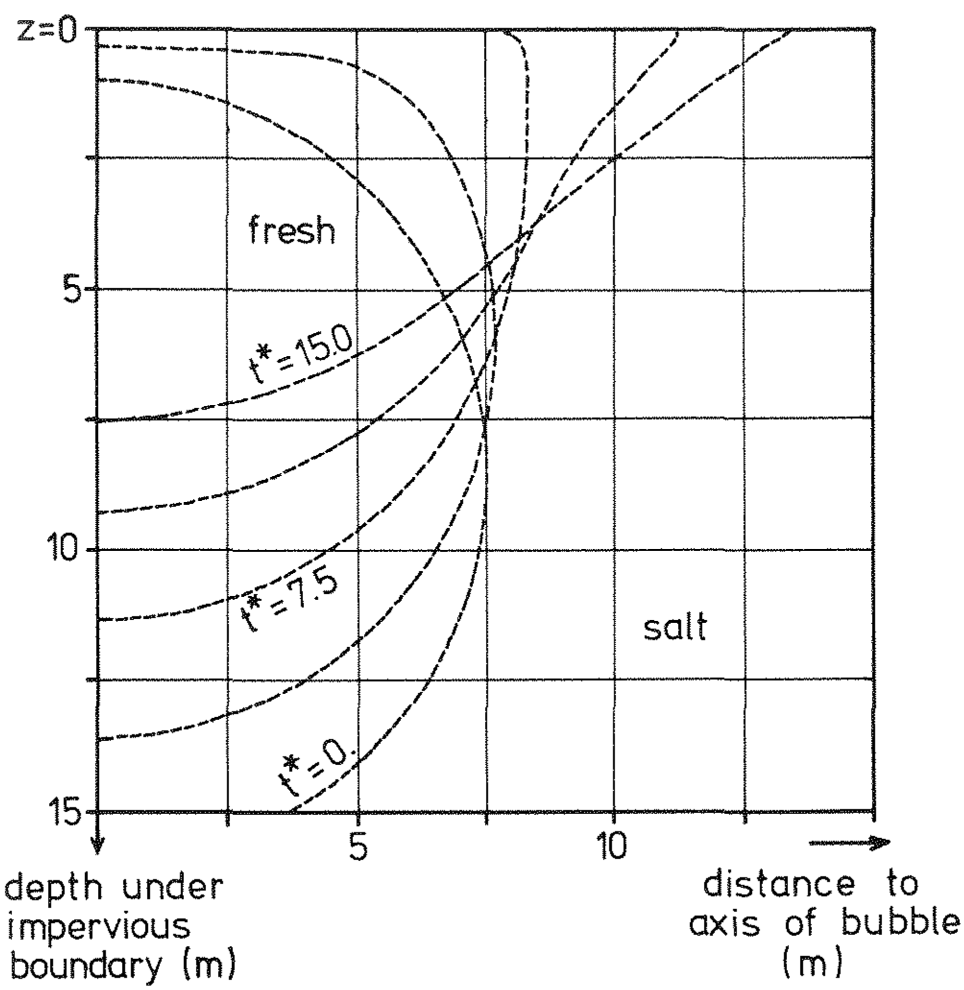


Fig. 4 - Motion of a fresh water bubble rising in a semi infinite salty aquifer with impervious boundary at z = 0.

Agreement with mathematically obtained results is exact. The foreign fluid (if an ellipsoid) moves as a rigid body slowly displacing the native fluid. Noteworthy in this connection is the problem of undeterminacy. Most researchers are familiar with the phenomenom of interfingering instability. When a fluid is displaced by a less viscous one the interface is not stable. Irregularities will grow. This and other viscosity effects can be significant when injecting surface water with varying temperatures. Especially close to wells where flow velocities can be large. In our analysis however viscosity differences are ignored.

Other undeterminacy phenomena exist when heavy fluids are on top of lighter ones. Any irregularity of the interface will grow because of interface instability. In fact it is impossible to model this kind of displacement because timesteps for which the movement is stable cannot be found. The movement is dominated by whatever small irregularity that may exist both in nature and in the computermodel, leading to unpredictable or incorrect interface positions.

Another test is the calculation of a time dependent motion of a bubble of fresh water rising in a saline aquifer when it encounters an impermeable boundary. With the passage of time the upward movement of the lighter fluid is retarded. Eventually the fresh water spreads laterally along the top of the aquifer. The movement is plotted in Figure 4 as a function of t^* defined as α times t. Values of t^* are in meters. At $t^* = 0$ the bubble is assumed spherical.

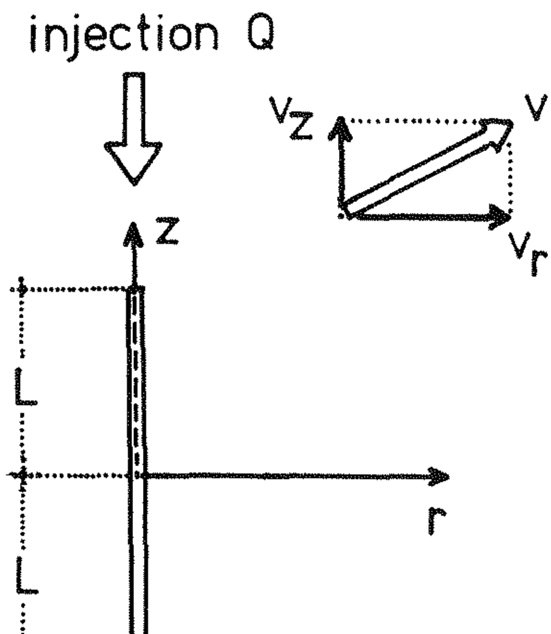


Fig. 5 – Velocity components of flow due to well recharge or abstraction.

5. WELL RECHARGE IN SEMI-INFINITE SALTY MEDIA

To calculate the motion of fresh water that is injected with wells the flow velocity components due to this injection are implemented in the axial symmetric computer program. It is assumed that along the filter screen the discharge is constant and equals Q/2L.

Van den Akker [1] elaborated the flow components in r and z direction by taking the derivative of the groundwater head for injection in a filter screen with length 2L. Another possibility is to write down the flow components for both directions due to a point source and then to integrate over the total filter screen length. This leads to the following less intricate formula (saving computer processing costs)

$$v_r = \left((L+z)/a + (L-z)/b \right) \cdot c/r$$

$$v_z = (1/b - 1/a) \cdot c$$

with

$$a = \mathrm{SQRT}\ (r^2 + (z+L)^2)$$

$$b = \mathrm{SQRT}\ (r^2 + (z-L)^2)$$

$$c = Q \ / \ (8\pi L n)$$

Using methods of images (to account for the impermeable boundary) and superposition the movement of fresh water injected in saline aquifers can now be calculated. To test the model computed displacement is compared with the observed displacement of saltwater as reported by e.g. Schuurmans and Van den Akker [13]. They described a field test with injection of fresh water in a completely saline aquifer bounded at the top by a rather impervious layer at a depth of 90 m. Injection discharge was 480 m^3/ day in a filter of 15 m starting at a depth of 101 m. Permeability for fresh water is estimated at 40 m/ day, porosity with respect to flow 38% and density difference 25 kg/m^3. Calculated is the motion of the interface if fresh water is injected for 60 days. When injection stops density effects cause the infiltrated bubble to rise with such velocity that within 3 weeks almost the complete filter screen is in saline water again, see Figure 6.

The model BUBBLE yields a result that shows acceptable agreement with the experiment described by Schuurmans and Van den Akker. Of course it should be kept in mind that sediment heterogeneity and dispersion are the principal factors to take into consideration when comparing both results.

It can be concluded that it turns out to be impossible to store water in thick saline aquifers if both permeability and density difference are large because subsequent attempts of recovery (with the same well) and storage times will lead to almost immediate entrance of native waters to the well.

6. FACTORS AFFECTING RECOVERY EFFICIENCY

Any plan to store water as described in this study should start with field tests, geologic investigations and use of predictive models to get an impression of recovery results. Exact values of recovery efficiency certainly depend on its definition. Recovery efficiency is the fraction of total injected water that can be abstracted before native water can be detected in the pumped water or as long as the quality meets standards for use. In literature various factors influencing recovery results are mentioned. These will be reviewed in short.

Mixing due to the fact that some of the liquid is not displaced so fast as the rest will cause a blurred transition zone between injected and native waters. This will also happen in the case of dead-end-pores where transport of salts can only take place by diffusion and not by flow or in the case of secondary permeability and porosity when fissure flow will occur. The extent to which this hydrodynamic dispersion is likely to cause brackish water is an important question which must be answered. Irregularities (inhomogeneities) play an important part in this connection. Gravitational segregation (reshaping or laydown of interface) occurs when two fluids with different density are in contact. With the passage of time the lighter fluid tends to rise compared to the heavier one. This effect is influenced by the density difference and by permeability. In this connection stratification and anisotropy seriously reducing vertical permeability should be mentioned. Pre-existing groundwater flow -sometimes called salt water flux- is unfavourable since it displaces the injected

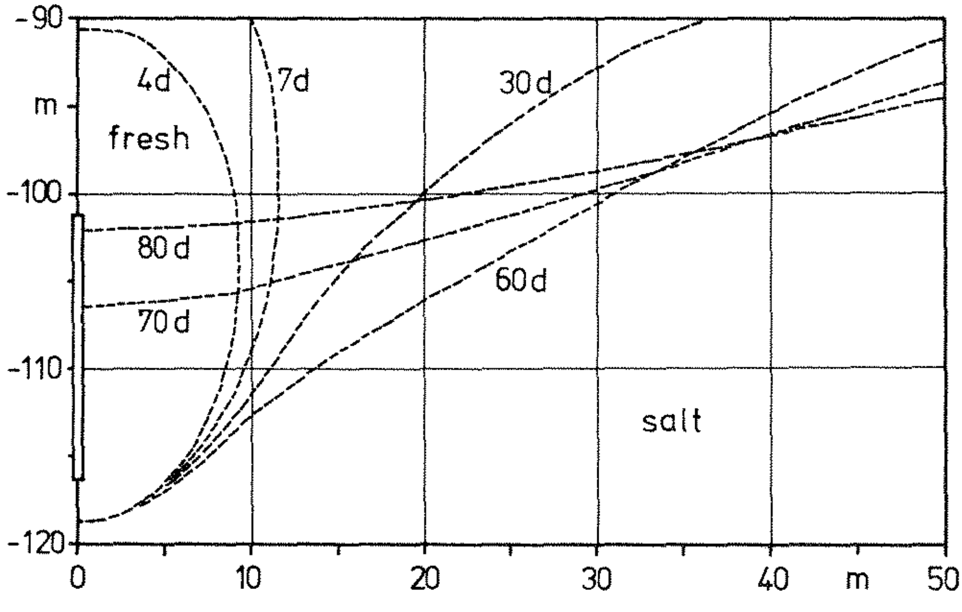


Fig. 6 – Motion of interface if fresh water is injected for 60 days.

water so that (part of) it cannot be retrieved. Aquifer dip can reduce recovery efficiency. A density difference will then cause the injected bubble to move in a «horizontal» direction. Injection rates do influence recovery results. If injection is large other unfavourable convective effects will be less harmful. However if storage times are large effects of density difference, aquifer dip and hydraulic gradients can again be serious. Other variables that do affect recoveries are aquifer thickness, cross flow over the upper and lower boundaries of the target-aquifer and chemical reactions between injected water and sediments. Various experiments subsequent to each other can also increase recovery efficiency («multicycle operation»).

7. CONCLUSIONS

Many reported laboratory results indicate that it is feasible to store fresh water in saline aquifers. However it should be kept in mind that actual field conditions that depart from idealized model assumptions can seriously reduce recovery results. Many field experiments show that dispersion in nature is much larger than in laboratory models. Calculations presented in this paper however indicate that density effects can be a much more important cause of poor fresh water recovery results than in dispersion. It can be concluded that before storage build-up in practice can be applied, a number of questions remain to be answered. Geologic and hydrogeologic investigations should lead to a profound knowledge of subsurface environment. Analytic models can quickly give an impression of recovery efficiencies. Use of numerical models that can take into account inhomogeneity and dispersion should just then be considered.

With some modifications the results of this study can also be applied to other research projects. Among these are injection of fluid waste or treated sewage and percolate flow near disposal sites. Vortex theory can enable us to predict behaviour of injected fluids in target – formations with low permeabilities or hydraulic gradients. Attention should then be centred on possible impact on environment.

ACKNOWLEDGEMENTS

This work is a result of a project «Hydrology of Recharge Well Systems» sponsored by the VEWIN research-program. VEWIN is the Association of Waterworks in the Netherlands.

Discussions with Prof. G. de Josselin de Jong and the assistance of Mr. W. Boerhout in preparing some of the computerplots, are gratefully acknowledged.

NOTATIONS

g acceleration of gravity (L/T^2)
Q strength of injection (L^3/T)
k hydraulic permeability (L/T)
L half the length of filter screen or dimension of length
M dimension of mass
n porosity with respect to flow (–)
r distance to axis of symmetry (L)
T dimension of time
t time (T)
t^* α times t (L)
v_r actual velocity component in r-direction (L/T)
v_z actual velocity component in z-direction (L/T)
z vertical coordinate (L)

α constant of gravitational segregation (L/T)
$\varkappa$ intrinsic permeability of sediments (L^2)
μ dynamic viscosity of fluid $(M/L/T)$
ρ density of fluid (M/L^3)
$\Delta\rho$ density difference (M/L^3).

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