

Analysis and Evaluation of Pumping Test Data

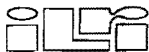
Second Edition (Completely Revised)

G.P. Kruseman
Senior hydrogeologist, TNO Institute of Applied Geoscience, Delft

N.A. de Ridder
Senior hydrogeologist, International Institute for Land Reclamation
and Improvement, Wageningen
and
Professor in Hydrogeology, Free University, Amsterdam

With assistance from
J.M. Verweij
Freelance hydrogeologist

Publication 47



International Institute for Land Reclamation and Improvement,
P.O. Box 45, 6700 AA Wageningen, The Netherlands, 1994.



The first edition of this book appeared as No. 11 in the series of Bulletins of the International Institute for Land Reclamation and Improvement/ILRI. Because the ILRI Bulletins have now been discontinued, this completely revised edition of the book appears as ILRI Publication 47.

The production of the book was made possible by cooperation between the following institutions:

International Institute for Land Reclamation and Improvement, Wageningen
TNO Institute of Applied Geoscience, Delft
Institute for Earth Sciences, Free University/VU, Amsterdam

First Edition 1970

Reprinted 1973

Reprinted 1976

Reprinted 1979

Reprinted 1983

Reprinted 1986

Reprinted 1989

Second Edition

Reprinted 1991

Reprinted 1992

Reprinted 1994

Reprinted 2000

The aims of ILRI are:

- To collect information on land reclamation and improvement from all over the world;
- To disseminate this knowledge through publications, courses, and consultancies;
- To contribute – by supplementary research – towards a better understanding of the land and water problems in developing countries.

© 2000 International Institute for Land Reclamation and Improvement/ILRI. All rights reserved. This book or any part thereof may not be reproduced in any form without written permission of the publisher. Printed in The Netherlands by Veenman drukkers, Ede

ISBN 90 70754 207

Contents

Preface

1	Basic concepts and definitions	13
1.1	Aquifer, aquitard, and aquiclude	13
1.2	Aquifer types	14
1.2.1	Confined aquifer	14
1.2.2	Unconfined aquifer	14
1.2.3	Leaky aquifer	14
1.3	Anisotropy and heterogeneity	14
1.4	Bounded aquifers	17
1.5	Steady and unsteady flow	17
1.6	Darcy's law	18
1.7	Physical properties	19
1.7.1	Porosity (n)	19
1.7.2	Hydraulic conductivity (K)	21
1.7.3	Interporosity flow coefficient (λ)	21
1.7.4	Compressibility (α and β)	22
1.7.5	Transmissivity (KD or T)	22
1.7.6	Specific storage (S_s)	22
1.7.7	Storativity (S)	23
1.7.8	Storativity ratio (ω)	23
1.7.9	Specific yield (S_y)	23
1.7.10	Diffusivity (KD/S)	24
1.7.11	Hydraulic resistance (c)	24
1.7.12	Leakage factor (L)	25
2	Pumping tests	27
2.1	The principle	27
2.2	Preliminary studies	27
2.3	Selecting the site for the well	28
2.4	The well	28
2.4.1	Well diameter	28
2.4.2	Well depth	29
2.4.3	Well screen	29
2.4.4	Gravel pack	30
2.4.5	The pump	30
2.4.6	Discharging the pumped water	31
2.5	Piezometers	31
2.5.1	The number of piezometers	32

2.5.2	Their distance from the well	33
2.5.3	Depth of the piezometers	37
2.6	The measurements to be taken	37
2.6.1	Water-level measurements	38
2.6.1.1	Water-level-measuring devices	40
2.6.2	Discharge-rate measurements	41
2.6.2.1	Discharge-measuring devices	42
2.7	Duration of the pumping test	43
2.8	Processing the data	44
2.8.1	Conversion of the data	44
2.8.2	Correction of the data	44
2.8.2.1	Unidirectional variation	45
2.8.2.2	Rhythmic fluctuations	45
2.8.2.3	Non-rhythmic regular fluctuations	46
2.8.2.4	Unique fluctuations	47
2.9	Interpretation of the data	48
2.9.1	Aquifer categories	48
2.9.2	Specific boundary conditions	51
2.10	Reporting and filing of data	53
2.10.1	Reporting	53
2.10.2	Filing of data	53
3	Confined aquifers	55
3.1	Steady-state flow	56
3.1.1	Thiem's method	56
3.2	Unsteady-state flow	61
3.2.1	Theis's method	61
3.2.2	Jacob's method	65
3.3	Summary	70
4	Leaky aquifers	73
4.1	Steady-state flow	76
4.1.1	De Glee's method	76
4.1.2	Hantush-Jacob's method	77
4.2	Unsteady-state flow	80
4.2.1	Walton's method	81
4.2.2	Hantush's inflection-point method	85
4.2.3	Hantush's curve-fitting method	90
4.2.4	Neuman-Witherspoon's method	93
4.3	Summary	97

5	Unconfined aquifers	99
5.1	Unsteady-state flow	102
5.1.1	Neuman's curve-fitting method	102
5.2	Steady-state flow	106
5.2.1	Thiem-Dupuit's method	107
6	Bounded aquifers	109
6.1	Bounded confined or unconfined aquifers, steady-state flow	110
6.1.1	Dietz's method, one or more recharge boundaries	110
6.2	Bounded confined or unconfined aquifers, unsteady-state flow	112
6.2.1	Stallman's method, one or more boundaries	112
6.2.2	Hantush's method (one recharge boundary)	117
6.3	Bounded leaky or confined aquifers, unsteady-state flow	120
6.3.1	Vandenberg's method (strip aquifer)	120
7	Wedge-shaped and sloping aquifers	125
7.1	Wedge-shaped confined aquifers, unsteady-state flow	125
7.1.1	Hantush's method	125
7.2	Sloping unconfined aquifers, steady-state flow	127
7.2.1	Culmination-point method	127
7.3	Sloping unconfined aquifers, unsteady-state flow	128
7.3.1	Hantush's method	128
8	Anisotropic aquifers	133
8.1	Confined aquifers, anisotropic on the horizontal plane	133
8.1.1	Hantush's method	133
8.1.2	Hantush-Thomas's method	139
8.1.3	Neuman's extension of the Papadopulos method	140
8.2	Leaky aquifers, anisotropic on the horizontal plane	144
8.2.1	Hantush's method	144
8.3	Confined aquifers, anisotropic on the vertical plane	145
8.3.1	Week's method	145
8.4	Leaky aquifers, anisotropic on the vertical plane	147
8.4.1	Week's method	147
8.5	Unconfined aquifers, anisotropic on the vertical plane	148

9	Multi-layered aquifer systems	151
9.1	Confined two-layered aquifer systems with unrestricted cross flow, unsteady-state flow	152
9.1.1	Javandel-Witherspoon's method	152
9.2	Leaky two-layered aquifer systems with crossflow through aquitards, steady-state flow	154
9.2.1	Bruggeman's method	155
10	Partially penetrating wells	159
10.1	Confined aquifers, steady-state flow	159
10.1.1	Huisman's correction method I	162
10.1.2	Huisman's correction method II	162
10.2	Confined aquifers, unsteady-state flow	162
10.2.1	Hantush's modification of the Theis method	162
10.2.2	Hantush's modification of the Jacob method	167
10.3	Leaky aquifers, steady-state flow	169
10.4	Leaky aquifers, unsteady-state flow	169
10.4.1	Weeks's modifications of the Walton and the Hantush curve-fitting methods	169
10.5	Unconfined anisotropic aquifers, unsteady-state flow	170
10.5.1	Streltsova's curve-fitting method	170
10.5.2	Neuman's curve-fitting method	172
11	Large-diameter wells	175
11.1	Confined aquifers, unsteady-state flow	175
11.1.1	Papadopulos's curve-fitting method	175
11.2	Unconfined aquifers, unsteady-state flow	177
11.2.1	Boulton-Streltsova's curve-fitting method	177
12	Variable-discharge tests and tests in well fields	181
12.1	Variable discharge	181
12.1.1	Confined Aquifers, Birsoy-Summer's method	181
12.1.2	Confined aquifers, Aron-Scott's method	185
12.2	Free-flowing wells	187
12.2.1	Confined aquifers, unsteady-state flow, Hantush's method	188
12.2.2	Leaky aquifers, steady-state flow, Hantush-De Glee's method	189
12.3	Well field	189
12.3.1	Cooper-Jacob's method	189

13	Recovery tests	193
13.1	Recovery tests after constant-discharge tests	194
13.1.1	Confined aquifers, Theis's recovery method	194
13.1.2	Leaky aquifers, Theis's recovery method	195
13.1.3	Unconfined aquifers, Theis's recovery method	196
13.1.4	Partially penetrating wells, Theis's recovery method	196
13.2	Recovery tests after constant-drawdown tests	196
13.3	Recovery tests after variable-discharge tests	196
13.3.1	Confined aquifers, Birsoy-Summers's recovery method	196
14	Well-performance tests	199
14.1	Step-drawdown tests	200
14.1.1	Hantush-Bierschenk's method	201
14.1.2	Eden-Hazel's method (confined aquifers)	205
14.1.3	Rorabaugh's method	209
14.1.4	Sheahan's method	212
14.2	Recovery tests	215
14.2.1	Determination of the skin factor	215
15	Single-well tests with constant or variable discharges and recovery tests	219
15.1	Constant-discharge tests	220
15.1.1	Confined aquifers, Papadopulos-Cooper's method	220
15.1.2	Confined aquifers, Rushton-Singh's ratio method	221
15.1.3	Confined and leaky aquifers, Jacob's straight-line method	223
15.1.4	Confined and leaky aquifers, Hurr-Worthington's method	226
15.2	Variable-discharge tests	229
15.2.1	Confined aquifers, Birsoy-Summers's method	229
15.2.2	Confined aquifers, Jacob-Lohman's free-flowing-well method	230
15.2.3	Leaky aquifers, Hantush's free-flowing-well method	231
15.3	Recovery tests	232
15.3.1	Theis's recovery method	232
15.3.2	Birsoy-Summers's recovery method	233
15.3.3	Eden-Hazel's recovery method	233

16	Slug tests	237
16.1	Confined aquifers, unsteady-state flow	238
16.1.1	Cooper's method	238
16.1.2	Uffink's method for oscillation tests	241
16.2	Unconfined aquifers, steady-state flow	244
16.2.1	Bouwer-Rice's method	244
17	Uniformly-fractured aquifers, double-porosity concept	249
17.1	Introduction	249
17.2	Bourdet-Gringarten's curve-fitting method (observation wells)	251
17.3	Kazemi's et al.'s straight-line method (observation wells)	254
17.4	Warren-Root's straight-line method (pumped well)	257
18	Single vertical fractures	263
18.1	Introduction	263
18.2	Gringarten-Witherspoon's curve-fitting method for observation wells	265
18.3	Gringarten et al.'s curve-fitting method for the pumped well	269
18.4	Ramey-Gringarten's curve-fitting method	271
19	Single vertical dikes	275
19.1	Introduction	275
19.2	Curve-fitting methods for observation wells	277
19.2.1	Boonstra-Boehmer's curve fitting method	277
19.2.2	Boehmer-Boonstra's curve-fitting method	279
19.3	Curve-fitting methods for the pumped well	280
19.3.1	For early and medium pumping times	280
19.3.2	For late pumping times	282
	Annexes	289
	References	367
	Author's index	373

because flow in the (saturated) capillary fringe above the watertable is neglected (Van der Kamp 1985).

Under favourable conditions, the early and late-time drawdown data can also be analyzed by the methods given in Section 3.2. For example, the Theis method can be applied to the early-time segment of the time-drawdown curve, provided that data from piezometers near the well are used because the drawdown in distant piezometers during this period will often be too small to be measured. The storativity S_A computed from this segment of the curve, however, cannot be used to predict long-term drawdowns. The late-time segment of the curve may again conform closely to the Theis type curve, thus enabling the late-time drawdown data to be analyzed by the Theis equation and yielding the transmissivity and the specific yield S_Y of the aquifer. The Theis method yields a fairly realistic value of S_Y (Van der Kamp 1985).

If a pumped unconfined aquifer does not show phenomena of delayed watertable response, the time-drawdown curve only follows the late-time segment of the S-shaped curve. Because the flow pattern around the well is identical to that in a confined aquifer, the methods in Section 3.2 can be used.

True steady-state flow cannot be reached in a pumped unconfined aquifer of infinite areal extent. Nevertheless, the drawdown differences will gradually diminish with time and will eventually become negligibly small. Under these transient steady-state conditions we can use the Thiem-Dupuit method (Section 5.2).

The methods presented in this chapter are all based on the following assumptions and conditions:

- The aquifer is unconfined;
- The aquifer has a seemingly infinite areal extent;
- The aquifer is homogeneous and of uniform thickness over the area influenced by the test;
- Prior to pumping, the watertable is horizontal over the area that will be influenced by the test;
- The aquifer is pumped at a constant discharge rate;
- The well penetrates the entire aquifer and thus receives water from the entire saturated thickness of the aquifer.

In practice, the effect of flow in the unsaturated zone on the delayed watertable response can be neglected (Cooley and Case 1973; Kroszynski and Dagan 1975). According to Bouwer and Rice (1978), air entry phenomena may influence the drawdown.

Although the aquifer is assumed to be of uniform thickness, this condition is not met if the drawdown is large compared with the aquifer's original saturated thickness. A corrected value for the observed drawdown s then has to be applied. Jacob (1944) proposed the following correction

$$s' = s - (s^2/2D)$$

where

s' = corrected drawdown

s = observed drawdown

D = original saturated aquifer thickness