Journal of Hydrology 525 (2015) 489–495

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Field scale minimization of energy use for groundwater pumping

David P. Ahlfeld *, Mikaela M. Laverty

Dept. of Civil and Environmental Engineering, University of Massachusetts Amherst, MA 01003, United States

ARTICLE INFO

Article history:
Received 2 December 2014
Received in revised form 30 March 2015
Accepted 31 March 2015
Available online 7 April 2015
This manuscript was handled by Peter K. Kitanidis, Editor-in-Chief, with the assistance of Xunhong Chen, Associate Editor

Keywords:
Groundwater
Management
Energy use
Optimization

SUMMARY

The limitations on an analytical solution to a groundwater management problem are tested with a field-scale problem and a modification to the analytical solution is proposed. The management problem minimizes the energy used for extracting water from the subsurface. The analytical solution depends on assumptions of linearity, steady state conditions, and adequate water demand to activate all wells and results in a stationarity condition that depends on initial lift and drawdown at each well. The field-scale problem is an aquifer in California with large historical drawdown. Testing of the analytical solution assumptions provides encouragement that the analytical solution may be useful to well-system operators for practical application to minimize energy consumption for pumping.

1. Introduction

Electrical energy consumption for groundwater pumping is substantial. It has been estimated by Water in the West (2013) that the United States uses roughly 1–2% of total electricity production for groundwater extraction. Assuming lift requirements of 150 ft (46 m), Burton (1996), estimated that a typical municipal water distribution system uses 0.6 MW h for each million gallons of water processed. Wolff et al. (2004) cite various estimates from California groundwater users for the amount of energy required to extract one million gallons of groundwater that range from 0.54 to 2.3 MW h. Bennett et al. (2010) provides a similar range of estimates; 0.9 to 2.9 MW h per million gallons of groundwater extracted. This energy is expended to lift water from an aquifer to the ground surface, overcome friction in pipes and pumps and pressurize the water for introduction into surface-based distribution systems or agricultural dispersal.

The energy required for lifting groundwater is often the largest energy component in a water supply system. Its dominance in energy consumption is exacerbated by the ongoing depletion of groundwater in many aquifers caused primarily by sustained pumping. The High Plains aquifer underlies parts of eight states. Water level declines of more than 100 ft (30 m) as compared to predevelopment levels have been observed in some areas; in other areas the saturated thickness has been reduced by half (Bartolino and Cunningham, 2003). In the Southwest United States, there have been water level declines of 300–500 ft in Arizona and Las Vegas has had up to 300 ft of groundwater level decline. Antelope Valley, California, (the focus of this case study) located on the western edge of the Mojave Desert, has had more than 200 ft of groundwater level decline, resulting in 6 ft of land subsidence (Leighton and Phillips, 2003).

Groundwater management models that combine simulation and optimization methods can be used to minimize energy costs in multi-well systems. The energy consumed by pumping at a well is related to the product of the pumping rate at the well and lift. Lift is the difference between the head in the well and the head at the point at which the water is discharged. In general, both the head in the well and the head at the point of discharge are nonlinear functions of pumping. In some cases, the lift can be approximated as a linear function of pumping. For these cases, the product of lift and pumping is a quadratic function of pumping rate.

To minimize pumping energy cost a typical optimization formulation will simultaneously consider pumping across a multi-well system. The sum of the products of lift and pumping for each well is a measure of total system energy cost. This sum is minimized by choice of pumping rates at the various wells. The problem includes constraints that place lower bounds on pumping at individual wells and requires that total withdrawal

* Corresponding author at: Dept. of Civil and Environmental Engineering, 18 Marston Hall, University of Massachusetts Amherst, MA 01003, United States. Tel.: +1 (413) 545 2681 (O).

E-mail addresses: ahlfeld@ecs.umass.edu (D.P. Ahlfeld), mikaelam@engin.umass.edu (M.M. Laverty).

http://dx.doi.org/10.1016/j.jhydrol.2015.03.065
0022-1694/

meets a specified demand. This formulation is described in detail in the next section.

Ahlfeld and Laverty (2011), abbreviated herein as A&L, showed that, under certain circumstances, an analytical solution to the pumping energy minimization formulation, solved in the context of a numerical groundwater model, exists. The analytical solution has the feature that a metric computed from the pre-pumping lift and the drawdown induced by pumping takes a constant value. The pre-pumping lift, L, is the lift at a well when all managed wells are off. The induced drawdown, s, is the additional lift at a well caused by operation of all wells. A&L showed that, for many cases, the metric $L/2 + s$ will take the same value at each well when the pumping, and associated drawdown, are optimal. The analysis approach used by A&L followed that used by Katsifarakis (2008) and Katsifarakis and Tselepidou (2009) who addressed the same problem using analytical groundwater models and superposition.

Proof of the analytical solution of A&L required an assumption that the head responds linearly to pumping and that total demand is sufficient to cause all wells to operate at some pumping level regardless of initial lift. A&L demonstrated their results on a small hypothetical problem showing that introducing nonlinear response (i.e. unconfined conditions) produced only a small variation in the $L/2 + s$ metric at the optimal condition. In the present paper, we further evaluate the limitations to the analytical solution presented by A&L. We modify an existing simulation model for a field site in California to produce a hypothetical model suitable for this evaluation. The modified model includes features of heterogeneity in hydraulic properties and boundary conditions that might be encountered in actual field scale problems. We use the modified model to examine cases in which demand is insufficient to force all wells to operate and a case in which unconfined conditions are present. We solve the optimization formulation using a Quadratic Programming algorithm.

In section two, the optimization formulation is described in detail along with an outline of the analytical solution of A&L. In section three, the California case study is introduced and the method of solving the optimization problem is described. In sections four and five the results, discussion and conclusions are presented.

2. Optimization formulations to minimize pumping energy

In this section, the minimize pumping energy formulation, which minimizes the product of pumping and lift, is presented. A brief review of past use of this formulation is presented. The analytical solution to the problem, as found by A&L, is presented and the limitations described.

2.1. Minimize energy formulation

The minimize energy formulation is constructed to select pumping rates to minimize the total energy use subject to a requirement that the total pumping meets demand and pumping rates be non-negative. For a single time period and multiple wells, the formulation is written as:

$$\text{Minimize } Z = \sum_{i=1}^{n} \alpha Q_i (H_i - h_i) \quad \text{such that } \sum_{i=1}^{n} Q_i = D \tag{1}$$

$$Q_i \geq 0 \quad \forall\, i = 1, \ldots, n$$

where Z is the objective function, n is the number of wells, Q_i is the withdrawal rate at well i, H_i is the reference elevation to which water will be lifted at well i, h_i is the head at well i, and D is the demand that must be met with pumping. The constraint on demand is stated as an equality; demand must be met, but the formulation will never pump more water than is needed to meet the demand. The final constraints set a lower bound on pumping; the analytical solution requires no upper bound on pumping except that implicit in the demand constraint. Each term of the objective function in (1) gives a measure of the energy required to lift water during a specified time period. The coefficient on each term, α, includes terms to convert from power to energy and takes the form

$$\alpha = \Delta t \rho g \tag{2}$$

where Δt is the duration of pumping, ρ is the density of the water and g is the gravitational constant. The coefficient α can also include friction loss factors, pump efficiencies, or any relevant conversion factors for units or electricity costs. Earlier use and analysis of this formulation has been conducted by Maddock (1972), Willis and Yeh (1987), Ahlfeld and Mulligan (2000), Theodossiou (2004) and Tsai et al. (2009).

The formulation can be written in terms of drawdown rather than head as noted in Fig. 1. Defining h_i^0 as the reference head at location i (e.g. the head without any pumping), the head at any pumping level can be described as $h_i = h_i^0 - s_i$ where s_i is the drawdown. Defining L_i, the initial lift at location i, as $L_i = H_i - h_i^0$, and substituting into the objective function in (1) yields

$$Z = \sum_{i=1}^{n} \alpha Q_i (L_i + s_i) \tag{3}$$

The hydraulic head in (1) and the drawdown in (3) depend upon the pumping rate decision variables. Using a Taylor series linearization of head the problem can be converted to a quadratic form. This is accomplished using response coefficients (Gorelick, 1983), so that the drawdown form of the objective takes the form

$$Z = \sum_{i=1}^{n} \alpha Q_i \left(L_i + \sum_{j=1}^{n} r_{i,j} Q_j \right) \tag{4}$$

where drawdown has been replaced with a linear function of pumping rates that utilize response coefficients $r_{i,j}$, which quantify the change in head at pumping site i with change in pumping rate at location j.

2.2. Analytical solution to the minimize pumping energy problem

For their analytical solution A&L consider steady state problems and eliminate the non-negativity constraint in Eq. (1) by assuming that demand will be high enough to cause all wells to be active.

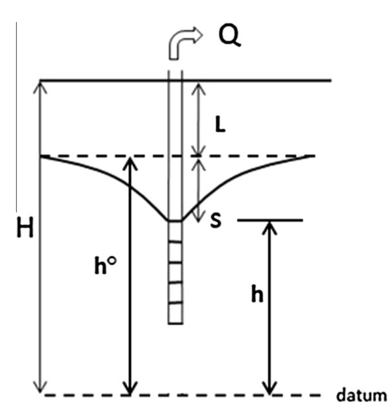

Fig. 1. Schematic of drawdown and definition of dimensions for reference head, lift and drawdown.