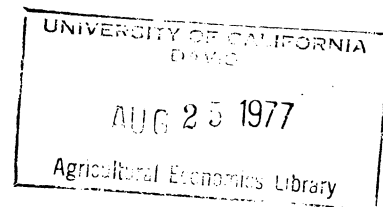Defining Upper Limits to

Groundwater Development in the Arid West

by

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and

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## I.  INTRODUCTION

As Western States attempt to respond to national needs for increased production of fossil fuels, the scarcity of water in this area looms as a major potential impediment; this is particularly true in the Rocky Mountain region wherein coal production is expected to increase by more than 500% (FEA, p. 200).  With few exceptions, surface water supplies in this area are totally developed.  Currently, efforts by state and regional planners to deal with the resulting dilemma -- pressing needs for rapid industrial development and water scarcity -- involve one or both of the following: reallocate water from agricultural to municipal/industrial uses, and/or develop and exploit groundwater stocks.  (Albuquerque Tribune, April, December, 1976, and Cummings and Gisser).

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In considering the possibility of rapid groundwater development in the Western States, one has ample cause for concern given this area's experiences with groundwater development over the past twenty years. The pattern of such developments has been almost consistently one of overdevelopment. This is to say that the scale of development has been out of proportion to the groundwater stock and natural recharge. The result has been rapid mining, and thus depletion of the stock. This pattern is seen in many areas overlying the Ogallala aquifer, particularly in the High Plains area with sub-areas facing the depletion of groundwater stocks within three years (Albuquerque Tribune, November, 1976). Depletion of groundwater stocks in southern Arizona has been the raison d'etre for the Central Arizona Project (Kelso, et. al.); depleted stocks have become an increasingly serious problem in western Kansas.[1]

The basic notion developed in this paper is that problems of the sort exemplified above might be avoided, or perhaps diminished, if at the outset groundwater development plans were considered in the context of the optimal steady-state level for groundwater stocks and rates of natural recharge. The "optimal steady-state stock" (denoted x*) is the level of groundwater storage at which mining optimally ceases, and withdrawals of groundwater are limited to natural recharge (w). If, prior to groundwater development activities, planners know x* and w for a given aquifer, the following kinds of policy-related questions can be addressed.

· Given alternative levels of development (permissible annual
withdrawal rates), for how many years can these withdrawal
rates be maintained? This is to say that, given initial
storage $x_o$ and the steady-state storage level $x^*$, the
difference $x_o - x^*$ can be mined (withdrawals in excess of
recharge): for a given annual rate of mining, m, the number
of years that m can be maintained is given by

$$T(m) = \frac{x_o - x^*}{m}$$

· The annual rate of groundwater withdrawals, u, consists of
mining and recharge, i.e., $u = m + w$. Each rate of mining
analyzed above implies a number of years $T(m)$ for which that
level can be maintained. For each m, then what is the impact
on local communities' use-rates u over $T(m)$ years, and what
are the impacts of water-use levels (which fall from u to w)
at the end of $T(m)$ years? With prior knowledge that a use-
rate can only be maintained for $T(m)$ years, what sorts of
legal-institutional arrangements might compensate for the
eventual (inevitable) fall in economic activity at $T(m)$ when
use-rates decline from u to w? What might be the ramifications
of establishing a system of water rights which expire, in a
staggered fashion, through time?

The questions given above are, of course, not comprehensive, but
are intended to be simply suggestive of the potential contribution to
the process of water planning that estimates for $x^*$ can make at the
initial stages of groundwater development.

In Section II, the general methodology for determining such steady-state levels in natural resource systems is developed, and data from a case study of groundwater use in the Estancia Valley (New Mexico) are used to exemplify the usefulness of the approach (Cummings and Gisser). Concluding remarks are given in Section III.

## II. DETERMINING STEADY-STATE GROUNDWATER STOCKS

A. The Conceptual Model. The basic structure of solutions for the optimal rate of extraction from natural resource systems has been the topic of a wide range of studies[2] and can be heuristically described as follows: Given an initial resource stock, periodic extraction is carried to the point where the value of the last unit extracted "today" equals the marginal, or incremental, value of a unit of the resource in storage. The value of a unit in storage is measured by such things as increased costs "pushed forward" to all future periods, and the value that the increment in storage can generate in future periods. With all future values discounted to the present, solutions for this class of problems normally involve high initial rates of extraction, with future extraction rates declining through time, eventually converging to the "flow" component of the resource system (natural recharge in the case of groundwater; convergence is to zero in the case of "exhaustible" resources).[3] The level of resource stocks that obtain when periodic extraction rates equal the flow-component of the resource system then remains constant into perpetuity; the resource system is said to be in a "steady-state", and this resource stock which remains unchanged through time is called the steady-state stock. Thus, the solution to the dynamic optimization

problem concerning the exploitation of a natural resource stock yields the steady-state stock and the _time_ at which the system optimally enters the steady-state.[4]

Solutions for dynamic optimization problems may become complex and costly, and may be impossible to obtain with the amount of regional detail required by planners. This is particularly true in early stages of groundwater development where hydrological and agroeconomic data may be extremely limited; this is to say that it is generally the case in early stages of groundwater development planning that the dearth of hydrological-agroeconomic data make efforts to apply "sophisticated" dynamic techniques a questionable exercise. Limited and weak data may be viewed as useful for only more cursory types of analyses. As shown in (Burt and Cummings), however, it is possible to calculate the dynamic optimization problem's steady-state stock without going through the dynamic optimization process.

For a system characterized by a resource stock x and a single control variable u, define u as total periodic groundwater use (total pumping) and x as the groundwater stock; if $\phi(u,x)$ is net losses of groundwater stocks per period, changes in groundwater stocks obey the difference equation, $x_{t+1} = x_t - \phi(u_t, x_t)$. Let G(u,x) measure periodic net incomes from groundwater use (e.g., net agricultural incomes from irrigation). As u increases, G increases, of course. Higher levels of x imply higher values for G for reasons described above, e.g., as x increases, water tables are higher, pumping costs are lower, and net agricultural incomes increase.

The general structure for the steady-state given by Burt and Cummings involves the simultaneous solution of the following equations (in what follows, $G_u$ is used to denote $\frac{\partial G(u,x)}{\partial u}$, $G_x = \frac{\partial G(u,x)}{\partial x}$, etc.);

$$G_u = \frac{\phi_u G_x}{(r+\phi_x)} \qquad (1)$$

$$\phi(u,x) = 0 \qquad (2)$$

where r is the discount rate. If w measures periodic net recharge to the aquifer and net recharge is independent of stocks, net decline in the groundwater stock is given by $\phi = u - w$ and (2) reduces to the simple result

$$u = w . \qquad (3)$$

To derive the steady-state groundwater stock x* from (1) and (3), one needs only estimates of G(u,x) -- how u and x determine incomes -- periodic recharge w, and discount rate r.

A simple extrapolation of pumping costs in a relatively high storage situation to a severely depleted one can be extremely misleading and even result in a negative value for x* in the solution of (1) and (3). Two economic forces will tend to make the marginal value of stocks increase rapidly as stocks are approaching exhaustion. First, wells will go dry in an irregular pattern because the water bearing strata will not be of uniform thickness throughout the basin. Second, drawdown at the individual wells during peak demand periods will result in water shortages during the critical periods of the season, especially from the larger bore wells.

The first phenomenon means that the groundwater stocks' function as a distribution system increases rapidly as stocks accumulate from the zero level, while the second implies that the intraseasonal storage function

of groundwater greatly improves as stocks increase from zero. Both of these economic considerations would tend to make $G_x$ increase rapidly as x goes to zero and thus force an equilibrium solution to (1) and (3) involving x* > 0.

B. An Application. To allow perspective as to the potential relevance of steady-state stock-levels, a somewhat hypothetical characterization of groundwater use in the Estancia Valley (some 40 miles east of Albuquerque, N.M.) is used as an example inasmuch as a recent study of that area (Cummings and Gisser) provides data required to estimate G(u,x).

Groundwater stocks in this essentially closed basin are currently some 2 million acre-feet,[5] with net annual recharge of 20,000 acre-feet. An estimate for net agricultural incomes based on budget studies of irrigated farms is given in (Cummings and Gisser). This work permits calculation of the function G in tubular form. Using parametric linear programming techniques, these data are used to estimate a continuous form for G by least squares fitting of a polynomial.[6]

$$G(u,v,x) = \$2512 + 13.3u - .1u^2 + 587.1v - 198.4v^2 + .73(uv)$$
$$76.6x - .16x^2 + 57(ux) + .72(vx) - 45(u^2x) \qquad (4)$$

In (4) u is the rate of groundwater use (in acre-feet/year), x is groundwater storage (in millions of acre-feet), and v is amortized annual capital costs (million dollars). Capital is included in G to reflect the possibility of substituting capital for water as groundwater storage declines. Ideally, capital would enter the problem as a stock; but insofar as groundwater stocks change slowly, and amortized capital costs in turn change slowly enough that the implied capital stock can be

depreciated at an economic rate consistent with the assumptions under-
lying the production function, the "flow" nature of v may be palatable.

The net decline in groundwater stocks in this case is simply a
function of annual withdrawals, or, with annual recharge, w, of 20,000
acre-feet,

$$\phi(u) = u - 20,000 \tag{5}$$

Consider now the following hypothetical problem. Suppose that
existing irrigation in this Valley is from surface waters. As a result
of energy developments in the Valley, or in other parts of the state,
planners are considering the development of the Valley's aquifer as
an alternative source of water for irrigation. Given the hydrological
characteristics of the Valley and its aquifer, what level of development
"should" be allowed?

Current storage of groundwater and annual recharge are known:
$x_o$ = 2 million acre-feet, and w = 20,000 acre-feet. The optimal steady-
state stock — the level of groundwater storage at which annual with-
drawals are optimally limited to recharge — is calculated using the
conditions (1) and (3), augmented by an equation to account for the
variable v, viz., $G_v$ = 0. Values for x* and v* for various discount
rates between 0% and 10% are given in Table 1.

Our hypothetical planners now know $x_o$ and x*, the difference
between which defines the upper limit on groundwater mining; thus, with
r = 5%, $x_o$ - x* = (2-.295) million acre-feet, and annual groundwater use is
limited to natural recharge after 1.705 million acre-feet has been mined.

What then are the ramifications of alternative levels of development in this Valley, where "levels of development" are represented by annual rates of water-use?  Suppose that one arbitrarily chooses for analysis the rates 83,000, 66,000, 56,000 (approximately the current rate of use in the Valley), 52,000, and 25,000 acre-feet per year.  Approximations for the associated annual levels of net farm income, regional income,[7] and the length of time that these income levels could be maintained before groundwater stocks fall to x* are as follows for discount rates of r = 0% and r = 5%.

Annual   rate of water use(acre-feet)

|  | 83,000 | 66,000 | 56,000 | 42,000 | 25,000 |
|---|---|---|---|---|---|
|  |  |  | (millions of $) |  |  |
| Net Farm Income: | $ 4.65 | $ 3.72 | $3.14 | $ 2.33 | $ 1.40 |
| Regional Income: | $14.88 | $11.9 | $10.05 | $ 7.46 | $ 4.48 |

Years Before The Steady-State

Annual rates of water-use (acre-feet):

| Discount Rate, r: | 83,000 | 66,000 | 56,000 | 42,000 | 25,000 |
|---|---|---|---|---|---|
| 0% | 5 | 7 | 8 | 11.9 | 18 |
| 5% | 20 | 26 | 30 | 41 | 68 |

With the data above, the following line of argument is available to the planner.  Given a zero discount rate, and allowing for 83,000 acre-feet of water-use per year, annual net farm and regional incomes will be on the order of $4.65 million and $14.88 million, respectively. But after 5 years, these income-levels will fall to those associated with use-rates set at natural recharge, i.e., annual net farm and

TABLE 1


Steady-State Groundwater Stocks and Optimal Levels

For Amortized Annual Capital Costs for

Selected Discount Rates*


| Discount Rate (r): | Steady-State Groundwater Stocks (x*) (million acre-feet) | Optimal Levels for Amortized Annual Capital Costs (v*) (million $) |
|---|---|---|
| 10.0% | .197 | $1.535 |
| 7.5 | .232 | 1.545 |
| 5.0 | .295 | 1.561 |
| 0 | 1.546 | 1.887 |


*Using G defined in equation (4), x* and v* are derived by solving the
following system of equations:

$$G_v = 0$$
$$G_u = G_x \cdot \frac{1}{r}$$
$$\phi(u) = u - 20,000 = 0$$

regional incomes will fall to $1.1 million and $3.6 million, respectively. With r = 5%, the higher income levels are maintained for 20 years.

With levels of development associated with annual use-rates of 56,000 acre-feet, net farm and regional incomes of $3.14 million and $10.05 million, respectively, are maintained for 8 to 30 years with r between 0% and 5%.

Knowledge as to the optimum steady-state stock-level thus places in perspective the magnitude and potential timing of changes in levels of economic activity, inevitably associated with declining groundwater stocks, given alternative levels of groundwater development.

## III. CONCLUDING REMARKS

Decisions as to the upper limits on groundwater development in any particular area are of course based upon the interplay of socio-economic, legal and political forces. With increasing water scarcity in the West, increasing attention will undoubtedly be given to the structure of legal and institutional arrangements that govern water use in general, and groundwater use in particular, and the resulting processes of development and change will surely require more and better data.

An effort is made here to suggest and exemplify computational techniques that provide protagonists in this process of change with information which may be critical for evaluating alternative strategies for groundwater development. The lines of argument developed here parallel the general philosophy which underlies adaptive control processes developed in recent years. The notion of an adaptive control

process centers on the information "feed-back" which can occur over time with operational experience. Thus, in the case of groundwater development, one begins with limited hydrologic information which is many times based on general information as to geological formations. Elementary hydrologic information is obtained only as drilling and pumping take place.

It follows then that early estimates for groundwater storage must be viewed as tentative, and subject to a process of modification as additional data becomes available. Such processes imply the need for relatively simple and flexible computational techniques, and a response to this need is the raison d'etre of the argument developed in this paper.

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## FOOTNOTES

[1] The overdevelopment of groundwater resources is certainly not a problem
peculiar to the U.S.: Similar problems in Northwest Mexico are described
in (Cummings, 1974).

[2] For a list of many of these studies, see the bibliography in Burt and
Cummings.

[3] It is important to recognize that natural recharge is not independent
of surface water development decisions, and there is often an oppor-
tunity to deliberately enhance recharge such that for the same total
flow of water consumption, a greater proportion comes from groundwater
(see Burt, 1976). The severe drought being experienced in the West
dramatizes the virtues of relatively greater dependence on groundwater.

[4] Technically, in many cases the steady-state is approached asymptotically,
in which case "time," as used above, is infinity.

[5] This is water of Class I quality (0–1000 ppm dissolved solids); for
simplicity, stocks of lower quality water are ignored.

[6] In terms of fitting the function (4) to data from Cummings and Gisser
a least-squares fit of a general quadratic in the three variables was
somewhat deficient. Third degree interactions were introduced into
the polynominal and only one term was of much consequence, namely,
linear storage times use-rate squared, $u^2x$. Although statistical
measures are not very relevant in this type of curve fitting, the
t-ratio on this interaction term was 9.4 and the adjusted R-squared

went from .968 to .981 with the addition of this variable into the quadratic. Clearly, the level of capital interacts with groundwater stocks in a sufficiently complex way that a simple cross-product term is inadequate. To reflect the "uneven bottom" problem of the aquifer, the model is structured such that land available for irrigation decreases by 10%, 25%, 40% as stocks fall from 2 million acre-feet to 1.58, 1, and .58 million acre-feet, respectively.

[7]Net farm income estimates are based on net farm income per acre-foot of water-use given in (Cummings and Gisser, Table 5 and C.5). These measures are not comparable with corresponding measures which one would derive from G (u,v,x) in (5), inasmuch as Cummings and Gisser treat x as a constant. Regional incomes are derived by applying a regional multiplier of 3.2 to net farm incomes.